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Environmental, Nutritional, and Physiological Factors Associated with Hoof Growth and Wear in Holstein Cows

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ENVIRONMENTAL, NUTRITIONAL, AND PHYSIOLOGICAL FACTORS ASSOCIATED WITH HOOF GROWTH AND WEAR IN HOLSTEIN COWS

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Dr. David J. Schingoethe — Date
Thesis Adviser

Dr. John G. Parsons — Date
Head, Dairy Science Dept.

DEDICATION

This thesis is dedicated to two women for instilling in me the importance of independent thought and encouragement to continually strive towards realizing my dreams. Thank you mother and grandmother.

Also, to my friend for his love, encouragement, and understanding. Although the hours we have spent apart are many, I have never felt alone. Thank you Chuck.

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Abstract

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Environmental, nutritional, and physiological parameters associated with hoof growth and wear were evaluated using data from 140 Holstein cows in five herds. Growth and wear of the dorsal and lateral regions of the front and rear outside claws were measured at approximately 2 mo intervals over a 14 mo period. Housing facilities varied from continuous confinement on concrete to confinement in dirt lots and included loafing sheds, free stall barns, and one comfort stall facility with rubber mats. Lateral hoof regions grew 24% faster than dorsal regions in the front and 20% faster in the rear hooves. Rear hooves grew 10% faster in the dorsal and about 6% faster in the lateral areas than the front hooves. Dorsal regions consistently wore at a lower rate than lateral regions. Hoof wear of the lateral area was less in front hooves than in the rear, but dorsal region wear was similar for front and rear hooves. Cows housed in free stall systems exhibited slower rates of hoof wear than animals housed in dirt pack loafing sheds and comfort stalls. Hoof growth was not as greatly influenced by housing type. Rates on hoof growth and wear increased with increasing photoperiod and ambient temperature. Reproductive efficiency, sire line, and type evaluations did not influence hoof growth or wear. Older animals exhibited slower

rates of growth and wear in the lateral region of rear hooves. Hooves grew more slowly in early lactation than in late lactation. Increased dietary sulfur intake was related to increased hoof growth and decreased hoof wear. Increased fiber intake was also related to increased hoof growth and tended to be related to decreased hoof wear.

LITERATURE REVIEW

Introduction

Dairy cattle used to be maintained on pasture operations; however, in order to maximize the efficiency of available resources, dairy cattle are increasingly being confined on concrete in free stall or comfort stall housing systems. Confinement housing has numerous advantages over pasture operations such as allowing a greater utilization of land resources and improved labor efficiency through increased mechanization. Along with the benefits obtained through the use of such systems, disadvantages include a rising incidence of feet and leg problems.

Harmon et al. (54) examined the reasons associated with the culling of 2,266 Jersey cows from a North Carolina dairy herd. At the beginning of the study, animals had been switched to a total confinement system. The survey included the period from January, 1968 through April, 1977. The primary reason for culling was low milk production. Although 24% of the animals were culled for this reason, feet and leg problems accounted for 18.5% of the animals being removed from the herd.

In a survey of the veterinary services provided to the University of Illinois dairy herd, feet and leg problems accounted for 9% of the veterinary services (6). Allen (3) stated that when they changed from a 90 cow stanchion barn to a 300 cow free stall barn culling due to feet and leg problems surpassed culling due to either mastitis or reproductive problems. The change in housing had been accompanied by a switch from a pasture rotation to a total confinement feeding program.

During 1977, Russell et al. (87) surveyed 48 veterinary practices in the British Isles. The practitioners treated 7,526 cases of lameness in 1,821 herds containing a total of 136,800 animals. The average annual incidence rate of lameness was 5.5%. This figure included only lameness that was treated by veterinarians and did not take into account cases that were treated by the dairyman. Eddy and Scott (34) reported a lameness incidence rate of 7.3%. In this study, 1,256 cattle from 150 farms were treated. The authors estimated that if treatment by the dairyman was taken into account, the incidence rate may have been as high as 60% in some herds. Prentice and Neal (80) stated that on an annual basis, 30% of the dairy veterinary cases in a region of England were related to lameness or foot disorders. Dewes (30) reported an annual lameness incidence rate of 14% in four New Zealand herds.

The costs associated with feet and leg problems have traditionally included the cost of treatment, the value of lost production due to treatment and the cost of replacing an animal that was culled. However, the financial effects of lameness may be more far reaching than these. Lameness has been shown to result in decreased feed intake, body weight, and milk production (6). Presumably because an animal suffering from limb disorders is less willing to travel to the feed bunk and is less likely to be aggressive while feeding. Poor reproductive performance may also be associated with a lame condition. An affected animal may be less inclined to mount or stand to be mounted during estrus. Britt (18) reported on a client's farm and stated that although the dairyman's cows were cycling regularly and did not show a high uterine infection rate, the animals exhibited poor expression of estrus due to foot disorders. He estimated that foot problems resulted in a 10 to 20% decrease in conception rates.

Prentice and Neal (80) examined the feet of cows after they had been slaughtered. They reported that 76% of the cows' feet showed some abnormalities and about one-third of the lesions could have resulted in lameness. Decreased milk production and reproductive performance have long been recognized as the major causes of voluntary culling (1, 2, 16, 17, 77, 103). Foot and leg disorders are now being recognized as factors contributing to milk production and reproductive efficiency decreases.

Anatomy and Histology of the Hoof

The anatomy of the hoof has been reviewed extensively by Hahn (48), Frandson (39), Sisson and Grossman (94), and Stump (98) among others. In order to understand the details in this review, a brief description of the anatomy and histology of the bovine hoof is included.

The hoof is the cornified epidermal layer covering the distal end of the digit. The bovine has a cloven hoof consisting of the outside or lateral claw and the inside or medial claw. The hoof is avascular and does not have a nerve supply. Functions of the hoof are to protect the distal digit from environmental agents and to support the body weight of the animals. There are three major and distinct horn tissues of the hoof: the wall, sole, and heel. Two complementary structures are the periople and the coronary band. Horn structures of the bovine hoof are depicted in Figure 1.

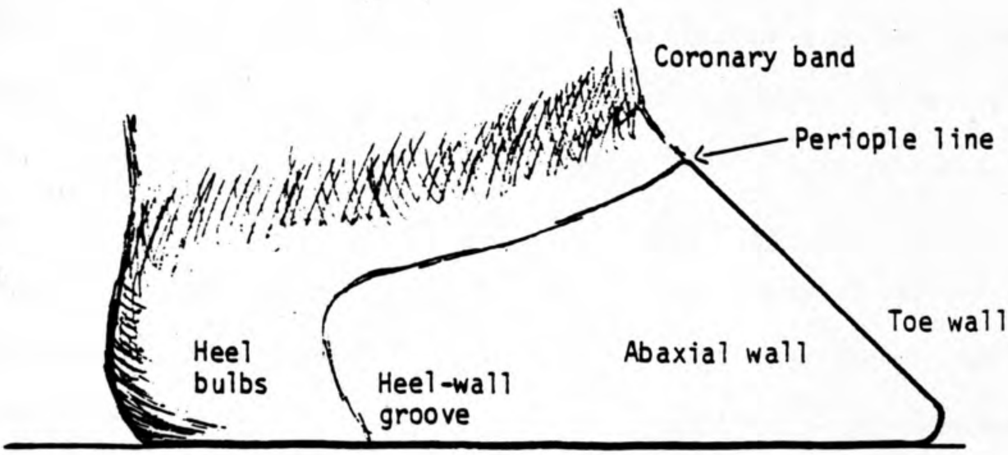
The coronary band joins the skin and the horn tissue of the hoof. It is actively growing and is highly innervated and vascularized. Due to the innervation of this area, it does not make a good reference point for measurement of the hoof wall.

The periople is a thin layer of soft pale tubular horn that covers the coronary groove. It is produced by the narrow perioplic band which is just above and concentric with the coronary band. The periople covers the proximal part of the hoof wall for a variable distance of 3/4 to 1 inch. The periople line is the clear regular end of the periople and can be used as a reference point for making measurements of the hoof wall.

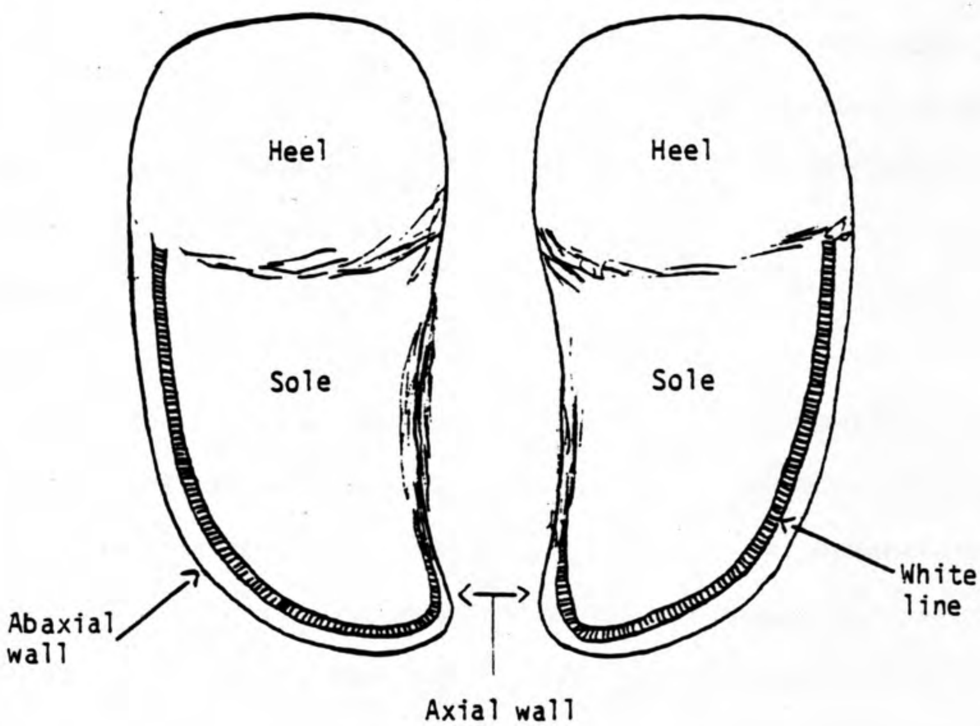
The majority of the animal's weight is distributed along the wall of the hoof. The outside or abaxial wall extends from the heel to the toe. It averages about 6 cm in length, although the thickness of the wall is variable, it averages approximately ½ cm. The thin layer of horny scales impart a smooth glossy appearance

Figure 1. Horn structures of the bovine hoof.

LATERAL VIEW



BOTTOM VIEW



when an animal is healthy. The axial or inside wall is a continuation of the abaxial wall at the toe and circles to the heel in the interdigital space. The axial wall is thinner and usually shows wrinkles or grooves which sometimes break and produce cracks.

The sole is a tubular horn tissue which covers the front part of the bottom surface of each claw. Normally, the sole is concave in shape and the hoof only touches the ground where the wall and sole meet. This concavity is necessary for proper function during locomotion. If the sole becomes flat, it is more susceptable to penetration, injury, and bruises. The epidermis of the nonrigid sole is connected to the laminae of the rigid abaxial and axial walls by a soft horn tissue which forms the white line.

The heel is the horn tissue which covers the bottom of the rear end of the hoof. It is the posterior continuation of the sole and laterally joins the abaxial and axial walls. The heel is the thickest and the softest of the three horn tissues of the hoof and is very important as a weight supporting and shock absorbing structure.

The corium or dermal layer of the foot consists of collagenous tissue with many elastic fibers. It is a highly vascularized tissue which furnishes nutrition to the germinal layer of the hoof and acts as an attachment between the hoof wall and the deeper structures of the foot. There are four separate and distinct corial regions: the perioplic, coronary, laminar, and solear.

The perioplic corium is a narrow band which lies in the perioplic groove above the coronary border of the wall. It has fine short papillae that curve downward and serve to furnish nutrients to the perioplic structure and produce a soft pale tubular horn.

The coronary corium occupies the coronary groove and has filiform papillae on the convex surface. The papillae project down into the overlying stratum germinativium and furnish the bulk of the nutrients that are necessary for keratin formation. The layer of stratum germinativium covering the papillae produces the hard tubular horn tissue which grows perpendicular to the coronary corium and distally towards the toe. Epithelial cells located over the interpapillary regions of the coronary corium produce a non-tubular cornified horn tissue. This tissue fills the area around the tubular horn tissue. Prentice and Wright (81) suggested that the tubules formed by the stratum germinativium act as a spring to absorb the weight of the animal as it is transmitted through the horn tissue.

The laminar corium is attached to the convex surface of the third phalanx by a modified periosteum. The primary sensitive or dermal laminae radiate from the corium. One edge of the laminae is attached to the corium and the other touches the tubular part of the hoof wall. Each primary lamina has 100 or more secondary laminae. The secondary laminae are parallel to the wall tubules and at right angles to the primary laminae forming a pennate arrangement. Each sensitive lamina has a corresponding insensitive or horny lamina which is attached to the tubular wall. The sensitive and insensitive laminae alternate and interlock to suspend the third phalanx within the hoof wall. The arrangement of interdigitating laminae allow the transmission of body weight to the wall of the hoof (97). When the hoof grows, the sensitive laminae remain attached to the periosteum of the third phalanx while the insensitive laminae move with the hoof wall.

The solear corium is attached to the periosteum on the volar (palmar) side of the third phalanx. The corium is covered by long papillar projections which are responsible for producing the short horn tubules of sole.

Histologically, the hoof is a modified continuation of the skin epidermis. The stratum basale is the deepest layer of the epidermis, it is a single layer of cells next to the corium. Cells that have migrated from the stratum basale and are undergoing keratinization are located in the stratum spinosum. The outermost layer of the stratum spinosum is called the "transitional" or "keratinization" zone. Cells in this zone are undergoing increased keratinization in which sulfhydral groups are being converted with the formation of disulfide bonds. The stratum basale and stratum spinosum together comprise the stratum germinativium. The stratum corneum is the heavy outer layer of keratinized cells that have migrated from the stratum germinativium.

Keratinization

Keratins are a large group of fibrous proteins which are the major constituents of horny tissues such as wool, hair, horn, and hoof. The amino acid composition of keratins is variable and tends to be dependent on the particular functions of the tissue. The α-keratins contain abundant amounts of amino acids which have hydrophobic R groups. The R-groups are located on the outside of the α-helix and give the α-keratins complete insolubility in water, at pH 7 and body temperature (62). A characteristic feature of keratins is their high cystine content. Production of cystine is via the oxidation of the sulfhydryl groups of cysteine molecules with the resultant formation of one disulfide bond and occurs in the keratogenous zone of the stratum spinosum (61). Larsson et al. (61) stated that in the formation of keratin, cystine can also be incorporated directly from the blood stream. The α-keratins contain adjacent polypeptide chains in the form of an α-helix. Cystine residues provide disulfide cross linkages between adjacent polypeptide chains. These covalent bonds give horn tissue its high mechanical strength and elasticity. Keratins also contain a high proportion of diamino and dicarboxylic acids which can have electrostatic attractions to form salt linkages. The weakening of keratins at pH extremes suggests that hydrolysis of salt linkages occurs in these ranges (26).

Lameness

Lameness has been defined as any restriction of the voluntary movement of an animal (46). Localization of lameness to the leg has been reported by several investigators (34, 87); however, the majority of lameness arises due to disorders of the foot. Russell et al. (87) reported that 88.3% of 7,526 cases of lameness were due to disorders of the foot rather than the leg. Eddy and Scott (34) surveyed lameness in 1,256 dairy cows and found that foot disorders were responsible for 92.2% of the lameness. Several other researchers have reported similar results indicating that 90% of lameness originates at the foot (6, 80). Russell et al. (87) reported that 84% of the foot lesions occurred in the hind feet and of these lesions, 85% were located on the outer claw. Dewes (30) also reported a higher incidence of lesions in the hind feet.

This higher incidence of hind lesions may be explained as follows. In normal locomotion, the front feet move in a vertical plane that is parallel with the cows midline. However, the hind feet are forced out of this vertical plane by the mammary gland. This may result in uneven loading and torsion on the hind feet. The hind feet are also subject to transitory loads that occur when the animal is mounted during estrus and are more likely to be subjected to fecal contamination (87).

Greenough et al. (46) categorized the causitive factors of lameness into four major categories of inheritance, infectious, environmental, and nutritional. In this review, the environmental and nutritional factors contributing to lameness will be examined. Hahn (48) presented an excellent review of the genetic and infectious factors causing lameness. Interest in these areas should be directed towards his dissertation.

Environmental Effects on Hoof Characteristics

The effect of housing on hoof growth and wear and the incidence of lameness has been reported by several researchers. Dewes (30) studied newly freshened animals as they entered the milking strings of four New Zealand dairies. Prior to freshening, the animals were on pasture and rarely encountered non-resisting ground surfaces. As part of the milking string, the animals traveled via concrete raceways to concrete floored housing pens for twice daily milkings. He reported that slightly more than 85% of the animals were first noted to be lame between 10 and 90 days postpartum.

Nocek (74) reported that the cow's natural habitat is a pasture situation. Normally feet do not need to be trimmed when animals are on pasture, as there is enough abrasion so that the hooves wear as they grow. He stated that animals confined totally on concrete in free stall housing had longer softer textured hooves than animals housed similarly, but with access to either dirt lots or pasture. Bostwick (14) stated that the cow's locomotion system was not designed to withstand the constant pounding and trauma that occurs when an animal is housed on an unyielding surface such as concrete. Kelly (57) reported that the most predominant housing system in the United Kingdom is cubicle housing, which is analogous to the free stall system of housing in the United States. He further reported that there was an increased incidence of lameness when animals were housed in cubicles as compared to animals housed in cow sheds or comfort stalls.

McGee et al. (68) conducted a trial with 64 cows over two lactations in two housing situations. One-half of the animals were housed totally on concrete. The other half were housed on concrete but had access to dirt exercise lots. Almost 60% of the animals confined exclusively to concrete developed swollen hocks and feet, whereas, none of the animals that had access off concrete showed either symptom. Moeller et al. (70) stated that animals housed on concrete continuously walked differently and experienced "concrete fatigue". They further concluded that animals on concrete require more frequent hoof care and showed less visible signs of estrus. A survey by Fessl (38) on lameness indicated that over 57% of the 3,143 animals treated had disorders related to their housing accommodations. The balance of the cases were due to either injury or infection. Chwojnowski et al. (25), as cited by Hahn (48), stated that when cattle had access to regular exercise in a dirt lot or pasture, they showed a lower incidence of hoof problems than cattle that were housed continuously on concrete.

Gilmore and Owen (42) measured the right rear hooves of nine

Ayrshires and 35 Holsteins over an 8 mo period following hoof trimming. Animals were confined for 23 h per day. Four Ayrshire cows and 18 Holsteins were housed in a free stall system while the remainder of the animals were housed in a tie stall barn. Animals housed in the free stall system showed a greater change in their hooves over the 8 mo period. This change was due to the faster rate of hoof growth exhibited by free stall housed animals. Cows housed in the tie stalls had hooves with a steeper dorsal angle and greater depth of heel. The authors suggested that a more intensive hoof management program, based on more frequent trimming is necessary when animals are housed in free stall systems.

Hahn (48) measured the hoof growth and wear of Holstein cows in several North Carolina dairy herds. Animals were housed in one of three types of housing: pasture, total confinement on concrete, or partial confinement on concrete. Animals confined on abrasive concrete exhibited a greater rate of hoof growth than cows on pasture. Confined animals also had hooves which wore 35% more than pastured animals. Gilmore (41) measured the dorsal length and angle and the depth of hoof of the rear hooves of 472 Holsteins in eleven Vermont herds. Four of the herds housed animals in tie stall barns, the remaining seven herds utilized a free stall housing system. He concluded that animals in free stalls had a shallower hoof angle as well as a shallower depth of heel. Animals housed in free stalls exhibited greater hoof length. Also noted was less variation in the measurements among tie stall herds as compared to a wider variation of measurements among free stall herds.

The solear surface of the hoof usually has a concave contour between the abaxial and axial sides of the hoof so that the surface of the sole does not normally make direct contact with the ground surface. The majority of the body weight is supported by the hoof wall. Direct contact with the ground surface is made at the junction of the hoof wall and sole along the white line. The laminae of the hoof serve to transmit the load absorbed by the hoof wall to the skeletal system. Reasearchers (30, 65) have reported a loss of sole concavity due to contact with abrasive surfaces such as concrete. Animals may become flat soled after they have been on concrete for only 3 to 4 mo. This condition will increase the likelihood of solear penetration by small objects and bruising due to direct contact with a hard unyielding surface.

Environmental moisture plays an important role in the function of the hoof and can directly affect the degree of hoof hydration (48, 58, 59). The elasticity of the hoof wall allows the absorption of forces which are applied to the hoof when direct contact is made with the ground surface. This elasticity is a function of the moisture content of the hoof. The hoof has the capacity to rapidly absorb and release water.

When animals are housed in confinement rather than on pasture, there is a higher probability for an accumulation of manure and excessive moisture at the ground surface. Several researchers (14, 58, 66, 86, 105) have reported a softening of hoof tissue when animals are exposed to excessive moisture. Excessive softening of the hoof can interfere with the absorption mechanism as well as increase the likelihood of penetration by foreign objects. Conversely, housing in too dry an environment can result in excessive drying of the hoof resulting in cracks in the hoof wall.

A survey (87) of the incidence of lameness in the British Isles indicated that most lesions occurred in the foot. The three most common lesions were foot rot (16.7%), white line abscess (15.6%), and sole ulcer (13.6%). Rowlands et al. (86) reported similar percentages of 15.8, 12.2, and 12.0 for foot rot, white line abscess, and sole ulcer, respectively.

In the US, foot rot has long been recognized as one of the major causes of lameness. Phlegmona interdigitatis (interdigital necrobaccillosis), commonly known as foot rot or foul-in-the-foot is an inflammation of the interdigital skin and underlying tissues (100). Severe lameness is commonly seen in animals with this condition. Fusobacterium necrophorum has been implicated as the major causative organism. Excessive moisture conditions, especially an accumulation of manure and urine, which can result in a softening of the hoof tissue also harbor the causative organism. Once the hoof softens, any injury may result in a bacterial infection. Polodermatitis circumscripta, commonly called sole ulcer, is a circumscribed lesion affecting the sole at the heel-sole junction (9, 87, 100). Rowlands et al. (86) reported that sole ulcer was more prevalent when animals were in confinement than on pasture.

Several researchers (9, 86) have stated that hard flooring, such as concrete, is more likely to cause bruising at the heel-sole junction.

Polodermatitis septica, commonly called white line abscess is caused by the disintegration of the fibrous junction between the wall and sole (9). Rowlands et al. (86) reported a lower incidence of this type of lesion when animals were housed in tie stalls as compared to free stalls. Baggot (9) associated this disease with the excessive hoof abrasion that occurs when an animal walks extensively on hard surfaces. They further implicated high environmental moisture levels as making the white line area more susceptible to disintegration and penetration.

The importance of adequate exercise, especially when animals are continuously confined, cannot be overemphasized as a preventitive measure against feet and leg problems (4, 7, 25, 48, 74, 100, 105). Since veins are surrounded by skeletal muscles, contraction of the muscles during activity compresses the thin-walled veins and assists in venous return. Also, when the animal takes a step, pressure at the heel assists in the movement of blood trapped in the venous plexuses under the corium (47). During quiet standing, gravitational forces can cause a pooling of blood in the veins of the legs.

Several researchers (91, 92) have studied the effect of housing animals on slotted floors on hoof characteristics. They reported that slotted flooring causes an uneven pressure and non-uniform load on the claws of the hoof. This results in qualitative changes in the horn tissue of the sole. Schmoldt and Heyden (92) reported that active deformation of the claws occurred when calves were moved to new slotted floor housing.

A seasonal effect on the growth of modified epidermal structures such as hoof, wool, and hair tissues has been reported by several researchers. Hahn (48) reported that hoof growth and wear were slowest during the winter months of January through March. During the summer months of June through August hoof growth and wear were at their highest points. Growth and wear during the summer was more than double the rate that occurred in the winter. Increased hoof growth corresponded to periods of increasing photoperiod, likewise periods of decreasing photoperiod corresponded to decreased hoof growth and wear. There was also a close relationship between hoof growth and wear and environmental temperature.

Clark (26) measured hoof growth during four periods which ranged between 70 and 90 days in length. Hooves of all cows showed the greatest rate of growth between April 10, 1979 and June 28, 1979. During this period, photoperiod increased and reached a maximum peak. The slowest period of hoof growth was reported during the late fall and winter months in which hours of daylight decreased and became minimal. Nocek (76) stated that 34% of the growth of the hoof occured during the spring and summer months. Rate of hoof growth decreased as the length of daylight decreased.

Wheeler (102) observed that both hoof and wool growth of Merino ewes in Australia were maximal during the period from early January through mid-March. The lowest rate of growth was reported to occur during early May and late August. Although this data would seem to contradict data presented previously, it must be remembered that summer months in the southern hemisphere correspond to the winter months of the northern hemisphere. Birrell (13) reported a similar trend in the rate of wool growth. Ryder and Stephenson (89) summarized several Australian research trials pertaining to the effects of photoperiod on wool growth and reported that there was active wool growth during the period of increasing daylight following the spring equinox. The rate of growth remains active until the autumn equinox, which preceded the period of decreasing photoperiod. Doney (31) reported that the rate of wool growth varied throughout the year, but followed a sinusoidal curve which was influenced by daylight.

Yeates (107) reported an experiment in which polled Shorthorn cattle were divided into two groups. The control group was exposed to the natural daylight which occurred during winter. Experimental group animals were exposed to a lighting scheme which simulated summer photoperiod. Control animals had typical winter hair coats, while a shorter "summer-type" hair coat was evidenced by animals in the experimental group. Similar photoperiod effects on the rate of hair growth were reported in a trial conducted by Peters et al. (79). Dowling and Nay (32) and Hayman and Nay (55) also noted that bovine hair length and diameter followed a cyclic seasonal pattern.

The effect of temperature on the growth of keratinized tissues has been investigated by several researchers. Hahn (48) noted a clear relationship between hoof growth, wear, and temperature. He mentioned that the seasonal effect on hoof characteristics may be influenced not only by photoperiod and temperature, but also by seasonal changes in management, feeding routines, and animal behavior. When animals are exposed to low environmental temperatures, there may be a reduction in blood supply to the extremities because of peripheral vasoconstriction (47). Doney (31) noted that environmental temperatures influenced wool growth, possibly due to a change in skin temperature and blood supply to the skin. When Yeates (107) induced a summer-type coat in animals by exposing them to a lighting regime which mimicked summer photoperiod at winter temperatures, the seasonal cycle of keratinized tissue growth appeared to be most strongly related to photoperiod, but may be slightly modified by ambient temperatures. Entwistle (36) reported that the wool growth of tropical Merino sheep was unaffected by temperature.

Nutritional Effects on Hoof Characteristics

Nutritional effects on keratinized tissues have been discussed by several researchers. Doney (31) stated that the most important factor affecting wool growth is the sheep's plane of nutrition. Yeates et al. (108) indicated that a 10% increase in a sheep's feed intake would be expected to result in a corresponding change in fleece weight. Tropical Merino sheep on a low protein ration exhibited lower rates of wool growth as compared to animals receiving a high protein diet (36). Under good grazing conditions, the rate of wool growth increased almost linearly as the digestible organic matter intake increased (13). Efficiency of wool production decreased when animals became stressed or when herbage quality was low (13).

A high level of dietary protein has been reported to be necessary for proper keratinization (43). There was a positive correlation between the protein level in rations fed to Duroc Jersey swine and the rate of their hair growth (37). Since the amount of protein required by sheep for the production of wool is not particularly high, the addition of protein to low protein rations is likely to result in a more efficient rate of wool growth only if the ration originally contained less than 8% protein (89). Hintz (56) stated that a protein deficient ration can result in a decrease in the growth of equine hooves. Goodspeed et al. (45) fed 20 Thoroughbred colts growing rations for a 9 mo period. One-half of the animals received a daily supplement of 114 g of gelatin. There was no difference in hoof strength due to the addition of dietary gelatin. Milne et al. (69) observed that the addition of gelatin to rations had no effect on equine sole characteristics. Similar results have been reported by Butler and Hintz (22). The results of these three trials are not surprising. Although an increase in protein intake would be expected to result in increased hoof growth, gelatin is a poor quality protein which is especially high in glycine and notably low in methionine. The ratio of non-essential to essential amino acids is also high in gelatin.

Ryder (88), as cited by Hahn (48), reported that adequate dietary protein is necessary to form high quality horn tissues. However, he reported that the most important nutritional factor influencing horn growth is the concentration of essential amino acids in the horn corium. Cystine, cysteine, and methionine are found in abundance in hoof, hair, and horn tissues. For keratin production, these sulfur-containing amino acids would seem to be the most important. Doney (31) and Rook and Thomas (85) have reported that a variation in the availability of sulfur containing amino acids can influence the rate of fiber growth and wool composition.

Wright (106) reported that a dietary addition of .3% methionine or methionine hydroxy analog (MHA), or intraperitoneal injections of 1.5, 3.0, or 4.5 g of methionine increased the rate of wool growth of lambs receiving either an 8% or 12% protein ration. Langlands (60) injected D-L methionine into the abomasum of grazing sheep and increased wool growth as much as 40%. When animals received an intraperitoneal injection of two 14 g L-cystine pellets, wool growth increased 20 to 25%. Administration of MHA depressed wool growth. Doyle and Bird (33) fed Merino sheep

1.9, 3.8, 7.7, or 15.4 g/day of D-L methionine and observed similar wool growth and fiber diameter when comparing all supplemented groups to the control animals. However, animals receiving 3.8 g/day D-L methionine had a higher wool growth rate compared to animals receiving no supplementation. Starks et al. (95) fed a control ration containing .054% sulfur with 92% of the ration nitrogen content from urea. Treatment rations were supplemented with either elemental sulfur, sodium sulfate, or D-L methionine. Animals which received supplemental sulfur produced more wool regardless of the source of supplemental sulfur.

Clark (26) fed a control ration or a control ration plus 30 g MHA per day to lactating cows each for 180 days. Treatment means for hoof growth and wear were not different, except that MHA supplemented cows had higher (P<.01) rates of hoof growth during the period from April 10 to June 28. The author concluded that supplementation with methionine hydroxy analog to lactating cows in an effort to specifically increase hoof growth and durability was not recommended.

Nocek (76) suggested that diets for lactating cows should contain .20 to .22% sulfur (S) to maintain the integrity of the hoof. Sodium sulfate, calcium sulfate, and potassium sulfate were suggested as sources of supplemental sulfur. Bull (20) stated that rations should contain .25% sulfur on a dry matter basis. Sulfur deficient rations are more prevalent today due to the use of diets composed primarily of corn silage and corn grain. Corn grain contains .14% S, whereas alfalfa hay is .36% S.

There is a close relationship between dietary nitrogen and sulfur. Several researchers have suggested a dietary nitrogen to sulfur ration of 10 to 1. When the ratio is wider than this, nitrogen may not be completely utilized (5, 11, 82, 104). Sulfur supplementation is more likely to be needed when diets contain nonprotein nitrogen. Protein rich feeds are the usual source of dietary sulfur, when these feeds are replaced by nonprotein nitrogen, less sulfur is present in the diet. Also, when dietary sulfur levels are inadequate, the utilization of recycled urea nitrogen may be limited (71, 104).

Bird (12) reported that the addition of urea and sulfate to wheat straw, substantially improved organic matter intake, dry matter digestibility, nitrogen balance, and live weight gain in sheep. This response from the sheep was additional to results obtained when additional sulfur was not added. When cattle were fed similar rations, there was a slight but not significant improvement of nitrogen balance and live weight gain. He concluded that a nitrogen to sulfur ration of 15 to 1 was adequate for cattle, but that sheep could not tolerate that wide a ratio. When sheep were fed supplemental sulfur (.36 g/day) while being fed a low protein roughage supplemented with urea, there was an increase in microbial protein synthesis and a shift from a negative nitrogen balance (-2.38 g nitrogen/day) to a positive nitrogen balance (+.15 g nitrogen/day). Organic matter digestibility also increased.

Chalupa et al. (23) fed steers an 80 to 20 concentrate to roughage diet in which urea supplied 66% of the dietary nitrogen. The control diet contained .05% sulfur while experimental diets contained supplemental sulfur in the form of either sodium sulfate or elemental sulfur, to achieve a diet containing .13% S. When diets were fed ad libitum, weight gains and feed intakes were increased and feed to gain ratios were decreased with sulfur supplemented diets. Animals fed the .05% sulfur diet did not exhibit any deficiency symptoms; however, additional dietary sulfur was essential for optimum production. Thompson et al. (99) fed beef cattle diets containing two levels of sulfur (15 to 1 and 5 to 1 nitrogen to sulfur ratio) and four nitrogen sources (soybean meal, urea, starea, or urea plus alfalfa meal). They observed no differences in animal performance with any of the protein supplements. Feed intake was lower on the high sulfur diets, however, feed efficiency was improved.

Sulfur has also been shown to be effective in stimulating cellulose digestion. Bull and Vandersall (21) observed that sodium sulfate, calcium sulfate, and methionine hydroxy analog (MHA) supplementation increased in vitro bacterial growth, cellulose digestion, and lignocellulose digestion as compared with a sulfur deficient media. Barton et al. (10) concluded that .14 to .17% S as ration dry matter produced optimum cellulose digestion. Bouchard and Conrad (15) increased dry matter digestibility in lactating cows by supplementing diets containing .1% S to .18% S with either sodium sulfate or MHA. Both sulfur sources were equally effective.

The synthesis of keratinized tissues is influenced by the availability of dietary energy. Ryder and Stephenson (89) stated that the most limiting factor for wool growth is insufficient energy content of the ration. Wool growth rates are very sensitive to alterations in the intake of energy, the growth rate is proportional to the rate of energy intake. A reduction in energy intake has been reported to decrease the rate of equine hoof growth (56).

Conversely, if animals receive rations that contain excessive amounts of readily fermentable carbohydrates this may precipitate a foot disorder known as founder or laminitis. This condition is especially probable when there is an abrupt change in the animal's diet. An example of such an abrupt change would be switching from an all hay diet fed to a dry cow to a ration of corn silage and grain fed when the animal freshened.

Laminitis is an inflammation of the sensitive laminae of the hoof and can take an acute or chronic course. Cows that previously had acute laminitis are predisposed to lesions in the laminar border of the hoof (64). In chronic laminitis, there is an elongation of the hooves and concentric rings around the hooves are often seen. Permanent deformation of the hoof wall is possible.

Robinson et al. (84) reported that within 48 h ponies that had been fed a high starch ration developed acute laminitis. Harkema et al. (53) reported that 7 of 12 ponies fed a diet high in starch developed acute laminitis within 56 + 3.5 h after feeding. Three of the 12 died, apparently of shock. Of the other two, one was unaffected and one was euthanized.

Garner et al. (40) observed that 11 out of 12 horses showed acute laminitis within 40 h after ingesting a large quantity of grain. Morrow et al. (73) injected lactic acid intraruminally into lambs, within 12 to 24 h after injection the lambs showed signs of laminar inflammation. Several vascular changes, pooling of venous and capillary blood, edema, and lymphatic stasis, precipitated the laminar inflammation. Brent (17) reported that lameness often accompanied lactic acidosis in feedlot cattle.

The exact causitive agent for lameness associated with acidosis has not as yet been elucidated. A current theory suggested that a triggering of histamine production may precipitate laminitis. Histamines cause arteriolar vasodilation and increase capillary permeability (47, 75). Increased permeability increases the diffusion of capillary fluids from the circulatory system into surrounding tissues which results in edema (47, 83). Histamine release may also occur as a result of infections such as mastitis or metritis or due to environmental factors such as the trauma associated with walking on hard unyielding surfaces such as concrete (63, 75, 76, 83). Increased pressure on the sensitive laminae of the corium can result in laminar destruction and hoof deterioration.

Recent research with swine indicates that the incidence and severity of foot lesions and accompanying lameness may be decreased when animals receive diets supplemented with biotin. Brooks et al. (19) investigated the effect of biotin supplementation on the incidence of foot lesions in sows housed on concrete with a small amount of straw bedding. All sows showed some sort of foot lesions, such as cracks in the hard horn of the side walls and toes and heel erosion or cracking. Over a 6 mo period, sows receiving supplemental biotin showed a 28% reduction in the number of foot lesions. Similar improvement in foot health with biotin supplementation was reported by Money and Laughton (72). When gilts received a ration containing supplemental biotin, they developed fewer and less severe foot lesions than control animals. However, sows already affected with lesions did not show any benefit from biotin supplementation (78).

Webb et al. (101) fed 12 crossbred pigs from weaning to slaughter weight. One-half of the animals received supplementary biotin (1 mg D-biotin/kg feed) the other animals served as controls. They reported that supplemented animals had a significant increase in the compressive strength and hardness of hoof tissue at the mid-abaxial side wall region. They also stated that the leading edge of the hoof wall was significantly stronger than the side wall, however, there was no increase in either hardness or compressive strength at this site due to biotin supplementation. The authors also reported a significant decrease in the hardness of the heel bulb. Increased strength and hardness of the hoof wall and decreased hardness of the heel bulb may reduce the incidence of hoof injury.

Biotin is a sulfur containing water soluble vitamin that is a component of several enzymatic systems. Biochemically, biotin functions as a transient carrier of a carboxy group in carboxylation reactions (62). It has previously been assumed that addition of supplemental biotin to livestock rations was unnecessary, since adequate amounts are synthesized by microbes in the intestinal tract and traditional feedstuffs contain sufficient biotin. However, Ensminger and Olentine (35) stated that corn and oats are both poor sources of biotin containing 0 to .1 mg/kg biotin. He rated barley and soybeans as good sources containing .1 to 1.0 mg/kg biotin. Cunha (29) stated that horses with a biotin deficiency show a loss of hair and cracked hooves. He also reported that there is a transverse cracking of the soles and tops of the hooves of pigs suffering from a biotin deficiency (28).

In ruminants such as the dairy cow, the rumen microflora have been reported to synthesize adequate amounts of biotin. Church (24) stated that the supplemental feeding of biotin even for preruminant calves is questionable.

MATERIALS AND METHODS

Environmental, nutritional, and physiological parameters affecting hoof growth and wear were evaluated using data on 140 Holsteins in five herds in South Dakota and Minnesota. Hooves of cows were measured at intervals of approximately 2 mo over a period of 14 mo from March, 1983 to May, 1984. All measurements were performed by trained personnel.

Housing facilities and management differed among the herds (Table 1). Herd one animals were confined on concrete in a free stall housing system year round. Dry cows were housed in a separate concrete-floored free stall facility with access to a dirt exercise lot. Twenty-one of the 33 cows had their hooves trimmed on August 10, 1983. Cows in herd two had access to a dirt floored loafing shed. They had free access to exercise yards that had a minimum of concrete and a maximum of dirt flooring. Access to pasture was allowed continuously from June through September, 1983. During the dry period animals were housed in dirt lots. Hooves of all animals were trimmed on July 28, 1983. Cattle in herd three were housed in a comfort stall barn on rubber mats. They had access to a dirt exercise lot and pasture for a variable amount of time depending on the season. During the period from November through March, the cows had access to a dirt lot and pasture for 1 h per day. April and May and from mid-July through October, cows had access for 9 h per day. Twenty hours of access was allowed during the month of June and the first half of July. Dry

TABLE 1. Herd summary.

Herd	Number of cows	Type of housing system	Ground surface of housing system	Exposure to concrete and dirt surfaces	Date trimmed
1	33	Free stall	Concrete	Continuous concrete	8/10/83
2	32	Loafing shed	Dirt	Concrete exposure during milking and feeding	7/28/83
3	26	Comfort stall	Rubber mats over concrete	Variable concrete and dirt	5/25/83
4	28	Free stall	Concrete	Variable concrete and dirt	8/15/83
5	21	Loafing shed	Dirt	Concrete exposure during milking and feeding	--

cows were housed on a dirt lot. Hooves were trimmed by professional trimmers on May 25, 1983. Herd four was housed in a free stall barn with concrete flooring and had access to lots with both dirt and concrete ground surfaces. Dry cows were continuously on dirt flooring. Hooves of all cows were trimmed on August 15, 1983. Cows in herd five were continuously confined in loose housing on dirt surfaces and did not have their hooves trimmed. In herds 1, 2, and 4, hoof measurements were made immediately prior to and after hoof trimming, so that the monitoring of hoof growth and wear was continuous over the length of the trial.

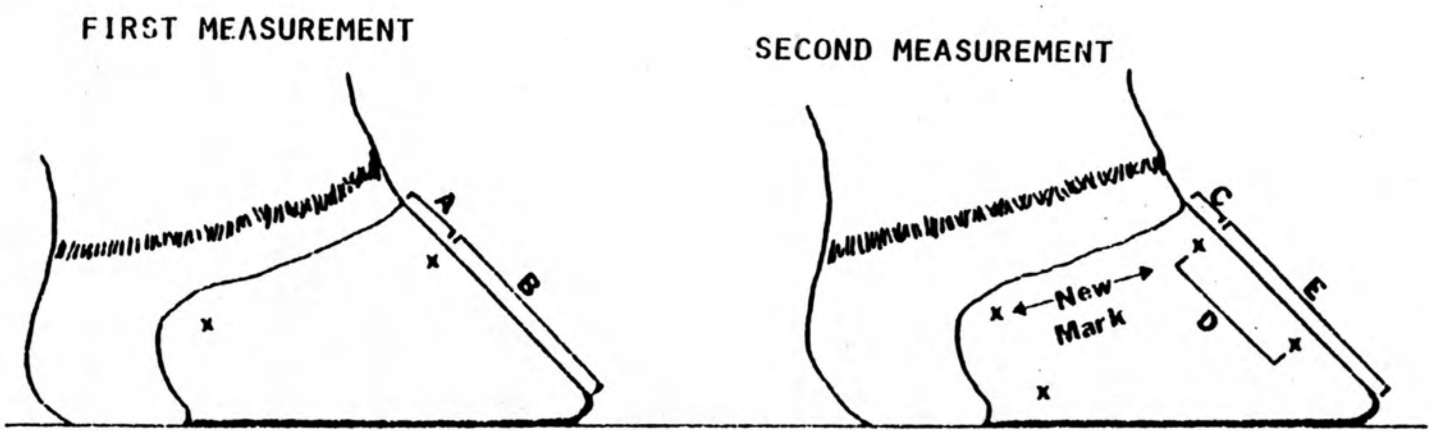
Hoof Measurements

Hoof growth and wear measurements were obtained according to the procedure developed by Hahn et al. (51). These procedures were reported to have high repeatabilities: .88 for dorsal growth, .80 for lateral growth, and .94 for both lateral and dorsal wear (51).

A soldering iron was used to burn an "x" on the abaxial wall in the dorsal and lateral regions of the outside or lateral claw of the front and rear hooves (Figure 2). The "x" was initially burned approximately 10 mm below the periople line and was used as a reference point for measuring the rate of hoof growth and wear. The distance from the periople line to the "x" was designated as hoof growth (A). Hoof wear (B) was designated as the distance from the "x" to the distal edge of the hoof, along

Figure 2. Identification of measurements used to estimate hoof growth and wear.

GROWTH = C + D - A; WEAR = B - (E - D)



the line of growth. A conventional divider was used in measuring the distances. Subsequent measurements of the same two distances yielded the displacement of the "x". Most of the time, a new "x" was burned 10 mm from the periople line during subsequent measurements so that a reference point remained on the hoof wall throughout the trial period. When a new reference point was made, the distance between the periople line and the new "x" was labeled hoof growth (C). The distance between the new "x" and the old "x" and the distance between the new mark and the distal edge of the hoof were designated D and E, respectively. When it was unnecessary to burn a new "x", subsequent measurements were made as for A and B and were labeled C and D.

Daily rate of hoof growth, using the notation of Figure 2, was obtained using the following formula:

$$\text{Daily growth (mm)} = \frac{C + D - A}{\text{days between measurements}}$$

Daily rate of hoof wear was calculated as follows:

$$\text{Daily wear (mm)} = \frac{[B - (E-D)]}{\text{days between measurements}}$$

Identification of Hoof Measurements

Utilizing the method previously described (51), the daily rates of hoof growth and wear were calculated on the lateral (outside) claws of the front and rear hooves.

The following rates of growth were obtained:

Dorsal growth front hoof (DGFH)

Lateral growth front hoof (LGFH)

Dorsal growth rear hoof (DGRH)

Lateral growth rear hoof (LGRH)

The following rates of wear were obtained:

Dorsal wear front hoof (DWFH)

Lateral wear front hoof (LWFH)

Dorsal wear rear hoof (DWRH)

Lateral wear rear hoof (LWRH)

Feed

Samples of feeds were obtained at each herd on the same day hoof measurements were taken. Dry matter was determined by drying samples for 72 h in a forced air oven at 57^{o}C. Dried samples were then ground through a 2 mm screen in a Wiley Mill before analyzing for crude protein and ash (8), acid detergent fiber, and neutral detergent fiber (44). Sulfur content of feeds was determined using atomic absorption spectrophotometry (8).

Miscellaneous

Climatological data, monthly minimum and maximum temperatures, and photoperiod data were acquired from Weather Research, Agricultural Engineering Department, South Dakota State University. Milk production information was obtained from monthly Dairy Herd

Improvement Association records corresponding to the date of hoof measurement. Reproductive data on each animal was secured directly from the herd owners. Type evaluations for classification traits and linearized descriptive traits were procured from Holstein-Friesian Association of America recording work sheets.

Statistical Analysis

Data were subjected to analysis of covariance (90).

Model I. The model for analyzing hoof growth and wear rates by sire effect:

$$Y_{ijklmno} = \mu+h_i+s_j+b_{k.ijlmn}(X_k-\overline{X}_k)+b_{l.ijkmn}(X_l-\overline{X}_l)$$
$$+b_{m.ijkln}(X_m-\overline{X}_m)+b_{n.ijklm}(X_n-\overline{X}_n)+E_{ijklmno}$$

where:

$Y_{ijklmno}$ = is the dependent variable, rate of hoof growth or wear,

μ = population mean,

h_i = is the fixed herd effect,

s_j = is the fixed sire effect,

b_k = is the partial regression due to age,

b_l = is the partial regression due to photoperiod,

b_m = is the partial regression due to minimum temperature,

b_n = is the partial regression due to maximum temperature,

$E_{ijklmno}$ = is the individual random error effect.

Model II. The model used for analyzing hoof growth and wear rates by reproductive efficiency traits:

$$
\begin{aligned}
Y_{ijklmnopq} = {} & \mu + h_i + b_{j.iklmnop}(X_j - \overline{X}_j) + b_{k.ijlmnop}(X_k - \overline{X}_k) \\
& + b_{l.ijkmnop}(X_l - \overline{X}_l) + b_{m.ijklnop}(X_m - \overline{X}_m) \\
& + b_{n.ijklmop}(X_n - \overline{X}_n) + b_{o.ijklmnp}(X_o - \overline{X}_o) \\
& + b_{p.ijklmno}(X_p - \overline{X}_p) + E_{ijklmnopq}
\end{aligned}
$$

where:

$Y_{ijklmnopq}$ = is the dependent variable, rate of hoof growth or wear,

μ = population mean,

h_i = is the fixed herd effect,

b_j = is the partial regression due to age,

b_k = is the partial regression due to photoperiod,

b_l = is the partial regression due to minimum temperature,

b_m = is the partial regression due to maximum temperature,

b_n = is the partial regression due to days dry,

b_o = is the partial regression due to services per conception,

b_p = is the partial regression due to calving interval,

$E_{ijklmnopq}$ = is the individual random error effect.

Model III. The model used to analyze rates of hoof growth and wear by nutritional, production, and subjective type traits categories. Components of each category were analyzed one at a time in order to find how they fit with the model:

$$Y_{ijklmno} = \mu+h_i=b_{j.iklmn}(X_j-\overline{X}_j)+b_{k.ijlmn}(X_k-\overline{X}_k)$$
$$+b_{l.ijkmn}(X_l-\overline{X}_l)+b_{m.ijkln}(X_m-\overline{X}_m)$$
$$+b_{n.ijklm}(X_n-\overline{X}_n)+E_{ijklmno}$$

where:

$Y_{ijklmno}$ = is the dependent variable, rate of hoof growth or wear,

μ = population mean,

h_i = is the fixed herd effect,

b_j = is the partial regression due to age,

b_k = is the partial regression due to photoperiod,

b_l = is the partial regression due to minimum temperature,

b_m = is the partial regression due to maximum temperature,

b_n = is the independent variables analyzed singularly in the model,

$E_{ijklmno}$ = is the individual random error effect.

Least square means were utilized to make preplanned comparisons (96). Differences were tested by the Waller-Duncan test (k-ratio=100, $P<.05$) when F-values were significant ($P<.05$) (96).

RESULTS AND DISCUSSION

Hoof Growth and Wear

Means of daily hoof growth and wear of the dorsal and lateral regions of the front and rear hooves appear in Table 2. Dorsal rates of hoof growth and wear were compared with corresponding rates obtained in the lateral hoof region (Table 3). Similarly, the rates of growth and wear of the front hoof were compared with the corresponding values obtained from the rear hoof (Table 3).

Hoof growth rates in the lateral region were greater ($P<.0001$) than dorsal growth rates for both the front and rear hooves of all cows throughout the trial. Clark (26) also observed greater growth rates for lateral than for dorsal regions of rear hooves, but noted similar growth rates for lateral and dorsal regions of front hooves. When comparing dorsal and lateral growth rates, Hahn (48) reported that the lateral region of the hoof grew about 20% faster than the dorsal region for the front and rear feet. Similar results were obtained in this trial as the lateral region grew 24% faster than the dorsal region in the front hoof and 20% faster in the rear hoof. Simon and Leemann (93), as cited by Hahn (48), and Gilmore and Owen (42) reported similar trends in the rate of hoof growth.

Rates of both dorsal and lateral hoof growth were higher ($P<.05$) for the rear hoof than for the front hoof. Clark and Rakes (27) found that although the dorsal growth rates for the

TABLE 2. Daily hoof growth and wear.

	Growth				Wear			
	Dorsal		Lateral		Dorsal		Lateral	
Hoof	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	(mm)							
Front	.127	.115	.158	.124	.092	.090	.108	.106
Rear	.140	.107	.168	.102	.087	.084	.121	.112

TABLE 3. Comparison of dorsal and lateral rates of daily hoof growth and wear and comparison of front and rear hooves.

Variable	Traits compared[a]	Mean	SE	T	P>T
		(mm)			
1	DGFH - LGFH	-.030	.004	-7.50	.0001
2	DGFH - LGRH	-.029	.004	-7.01	.0001
3	DWFH - LWFH	-.016	.004	-3.76	.0002
4	DWRH - LWRH	-.035	.005	-7.64	.0001
5	DGRH - DGRH	-.012	.005	-2.47	.0136
6	LGFH - LGRH	-.011	.005	-2.13	.0331
7	DWFH - DWRH	.005	.004	1.31	.1904
8	LWFH - LWRH	-.014	.005	-2.82	.0050

[a]DGFH = dorsal growth front hoof, LGFH = lateral growth front hoof, DGRH = dorsal growth rear hoof, LGRH = lateral growth rear hoof, DWFH = dorsal wear front hoof, LWFH = lateral wear front hoof, DWRH = dorsal wear rear hoof, LWRH = lateral wear rear hoof.

front and rear hooves were not significantly different, there was a tendency for faster growth in the rear feet. Hahn (48) reported that rear hooves grew 9% faster in the dorsal region and 7% faster in the lateral area, than front hooves. In this study, rear hooves grew 10% faster in the dorsal and about 6% faster in the lateral regions than the front hooves.

Growth rates in dorsal and lateral areas of front hooves were highly correlated (r=.55) with one another, as were corresponding regions of the rear hoof (r=.38). In future studies, fewer growth measurement, either in the lateral or dorsal area rather than in both regions may be more practical and efficient without sacrificing any accuracy.

The rate of hoof wear was less (P<.001) in the dorsal region than in the lateral region of the hoof. This difference was exhibited by both the front and rear hooves of all cows throughout the trial. Hahn (48) also found that the dorsal region wore at a slower rate than the lateral region. Clark (26) observed a tendency for greater wear in the lateral region, but differences between dorsal and lateral regions were not significant.

Hoof wear of the lateral region was less (P<.005) in the front hoof than in the rear, but dorsal wear was similar (P>.05) for front and rear hooves. As a point of interest, wear in the dorsal region was actually slightly greater on front than on rear hooves.

Sire Categories

Sires of all cows were categorized into one of nine groups as presented in Table 4. To be included in a particular sire grouping, the cow was either sired by the bull or by a son of that particular bull. There were no significant differences (P ranged from .60 to .99) in the daily rates of hoof growth (Table 5) or wear (Table 6) due to sire line. For this reason, and since over one-half of the animals would be deleted because they were sired by line 1 or 9, sire line was excluded from further analysis.

Gilmore (41) analyzed the dorsal hoof length of 472 cows which were sired by 46 sires. Each bull had four or more progeny with daughters in two or more herds. Differences ($P<.05$) were observed due to sire in average dorsal length. No significant differences in hoof growth or wear due to sire were detected in this trial; however, this may be due to the relatively limited number of animals in this study. Hoof growth and wear measurements of only 66 cows could be used when analyzing for sire differences. Sire line categories included not only the particular bull, but also his sons, which may have contributed additional variability to the sire data.

Reproductive Efficiency

Data were analyzed to determine the relationship between various measures of reproductive efficiency and the rates of hoof growth and wear. Number of inseminations per conception, length

TABLE 4. Sire line categories.

Sire line	No. of animals	Sire
1	63	Other
2	9	Paclamar Astronaut
3	7	Paclamar Bootmaker
4	12	Pawnee Farm Arlinda Chief
5	17	Round Oak Rag Apple Elevation
6	12	Hilltop Apollo Ivanhoe
7	5	No Na Me Fond Matt
8	4	Penstate Ivanhoe Star
9	11	Unknown

TABLE 5. Hoof growth by sire line.

Sire line	N	Hoof growth	SE	P>F
		(mm/day)		
		Dorsal growth front hoof		
1	360	.125	.006	
2	53	.110	.017	
3	41	.131	.018	
4	70	.124	.014	.99
5	94	.131	.014	
6	69	.125	.015	
7	29	.133	.021	
8	24	.128	.024	
		Lateral growth front hoof		
1	361	.159	.007	
2	53	.145	.017	
3	41	.143	.019	
4	70	.152	.015	.94
5	94	.157	.014	
6	69	.142	.016	
7	29	.168	.022	
8	24	.143	.025	
		Dorsal growth rear hoof		
1	361	.138	.006	
2	53	.123	.015	
3	41	.135	.017	
4	70	.134	.013	.95
5	94	.133	.012	
6	69	.129	.014	
7	29	.153	.020	
8	24	.144	.022	
		Lateral growth rear hoof		
1	361	.170	.006	
2	53	.160	.014	
3	41	.164	.016	
4	70	.170	.012	.86
5	94	.156	.012	
6	69	.164	.013	
7	29	.190	.018	
8	24	.155	.020	

TABLE 6. Hoof wear by sire line.

Sire line	N	Hoof wear (mm/day)	SE	P>F
Dorsal wear front hoof				
1	349	.091	.005	
2	51	.084	.013	
3	39	.094	.014	
4	70	.092	.011	.89
5	89	.108	.011	
6	66	.104	.012	
7	29	.083	.017	
8	23	.102	.019	
Lateral wear front hoof				
1	349	.114	.006	
2	51	.094	.015	
3	39	.092	.016	
4	70	.102	.012	.77
5	89	.110	.012	
6	66	.118	.014	
7	29	.116	.019	
8	23	.103	.021	
Dorsal wear rear hoof				
1	349	.085	.005	
2	51	.083	.012	
3	39	.104	.013	
4	70	.091	.010	.60
5	89	.082	.010	
6	66	.101	.011	
7	29	.097	.015	
8	23	.106	.017	
Lateral wear rear hoof				
1	349	.118	.006	
2	51	.111	.017	
3	39	.108	.018	
4	70	.140	.014	.69
5	89	.120	.014	
6	66	.132	.015	
7	29	.139	.021	
8	23	.142	.023	

of the dry period in days, and the interval between parturitions in months were designated as measures of reproductive efficiency. In all cases, there were no significant differences in hoof characteristics which could be related to the above measures of reproductive efficiency.

Reproductive traits (Table 7) averaged within acceptable ranges for all herds. Services per conception ranged from one to eight. Fifty-three percent of the cows settled on the first service. Dry periods ranged from 0 to 158 days. Calving intervals ranged from 10 to 24 mo. Thirty percent of the animals had calving intervals of 12 mo. Sixty-six percent of the animals began their subsequent lactation within 13 mo of their previous lactation.

McDaniel et al. (67) found that cows with shorter hooves had higher reproductive rates as measured by requiring fewer inseminations per conception and having fewer days open. Perhaps a significant effect of reproductive efficiency on hoof characteristics was not detected in this trial because animals had relatively high rates of reproductive efficiency.

Age

Cows in this trial ranged from 22 to 164 mo of age with a mean age of 52.6 mo (Table 8). Age of the cow affected ($P<.0005$) rate of growth in the lateral region of the rear hoof (LGRH). Age was negatively correlated ($r=.10$, $P<.0001$) with LGRH, in that as the age of the animal increased, the rate of LGRH decreased. Age

TABLE 7. Reproductive traits by herd.

Herd	Length of dry period	Inseminations per conception	Calving interval
	(days)		(mo)
1	54.5	2.1	13.0
2	65.9	1.9	13.4
3	62.7	1.4	12.9
4	66.4	1.5	13.8
5	55.0	2.5	14.0
Mean	61.3	1.8	13.4
SE	22.9	1.1	2.6

TABLE 8. Means of cow age and environmental factors by herd.

Herd	Age	Photoperiod	Minimum temperature	Maximum temperature
	(mo)	(min/day)	(^{o}C)	
1	43.0	731	-.4	10.0
2	42.2	738	-.2	10.8
3	49.8	738	-.2	10.9
4	34.8	738	.9	11.7
5	61.3	723	.4	9.2
Mean	52.6	729	-.4	10.0
Range	22.0 to 164.0	543 to 922	-19.5 to 16.8	-9.6 to 30.5

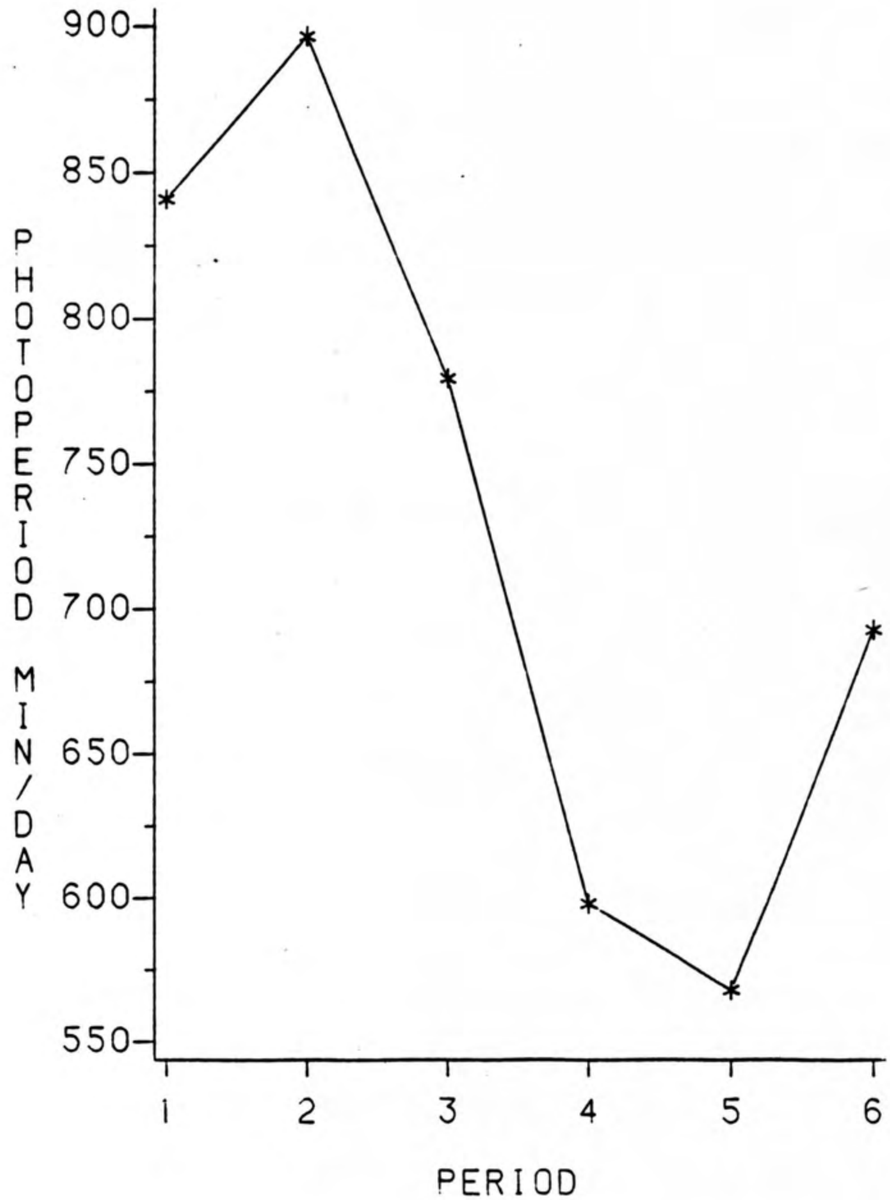
did not significantly affect growth in the other three regions. Clark (26) found no relationship between age and growth, while Hahn (48) reported that the rate of growth of front and rear hooves was reduced for cows in their second lactation as compared with cows in the first lactation.

Rate of wear in the dorsal region of the front hoof (DWFH) and the lateral region of the rear hoof (LWRH) were influenced ($P<.01$) by the age of the animal. Older cows showed a decrease in the rate of wear in these two areas as compared with younger cows ($r=.09$ for DWFH and $-.06$ for LWRH, $P<.05$). The rate of lateral wear of the front hoof and the dorsal wear of the rear hoof were not significantly influenced by age. Hahn (48) found a lower rate of wear in the front hooves for cows in their second lactation than in their first lactation. However, wear of the rear hooves were only slightly greater for second lactation cows. Overall, hoof length has also been shown to increase as the cow ages (49, 52).

Environment

Variations in photoperiod and ambient temperatures with measurement periods are illustrated graphically in Figures 3 to 5. Figures 6 to 8 graphically show the effect of environmental factors on hoof growth. Hoof wear as influenced by environment is presented in Figures 9 to 11. Length of photoperiod (Table 8), which ranged from 543 to 922 min/day, had a tendency to influence the rate of growth of the front hoof. Photoperiod affected ($P<.05$)

Figure 3. Minutes of daylight in relation to periods of hoof measurements.



900
850
800
750
700
650
600
550
PHOTOPERIOD MIN/DAY
1
2
3
4
5
6
PERIOD

Figure 4. Minimum daily ambient temperature in relation to hoof measurement periods.

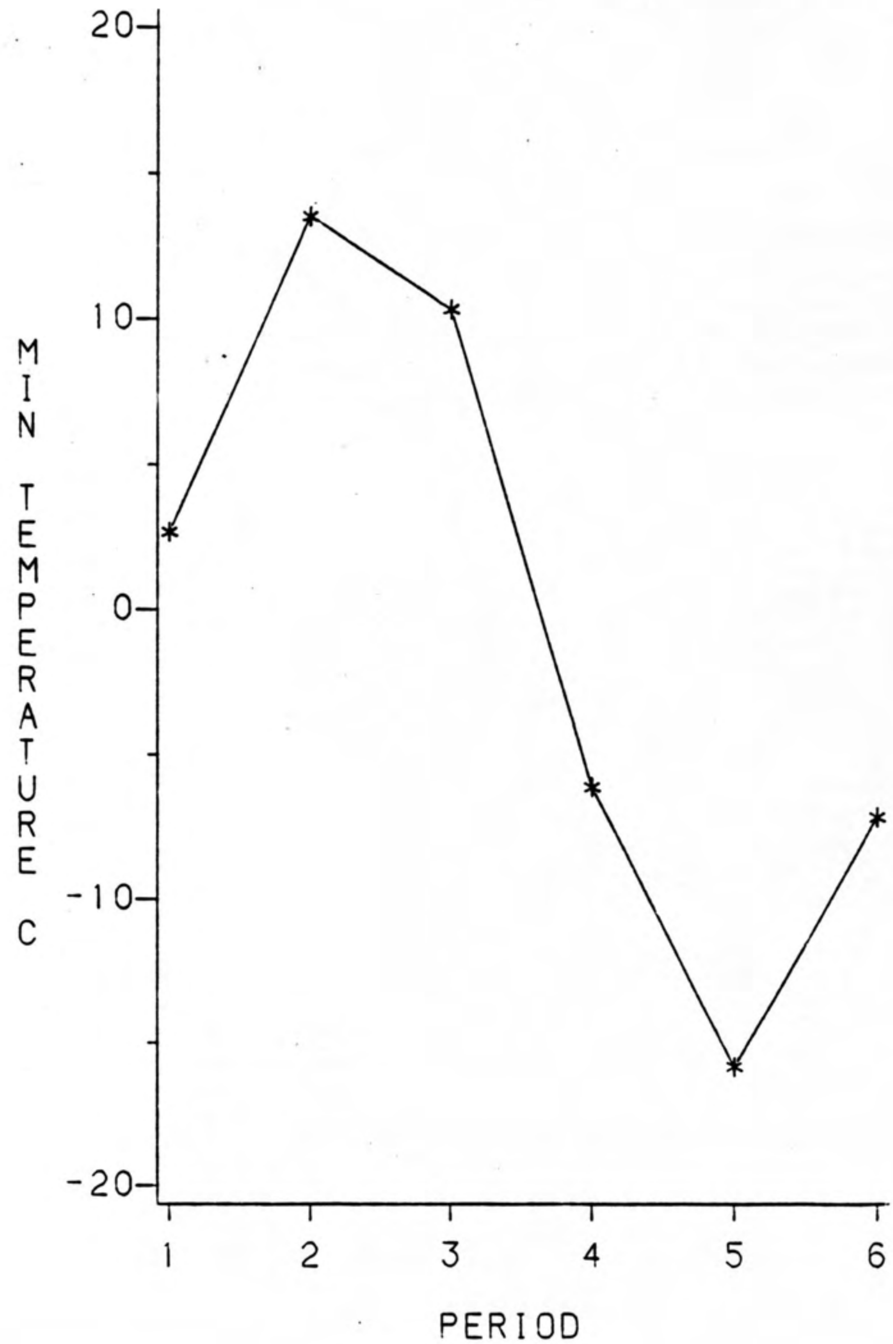

20
10
0
-10
-20
MIN TEMPERATURE C
1
2
3
4
5
6
PERIOD

Figure 5. Daily maximum environmental temperature in relation to periods of hoof measurements.

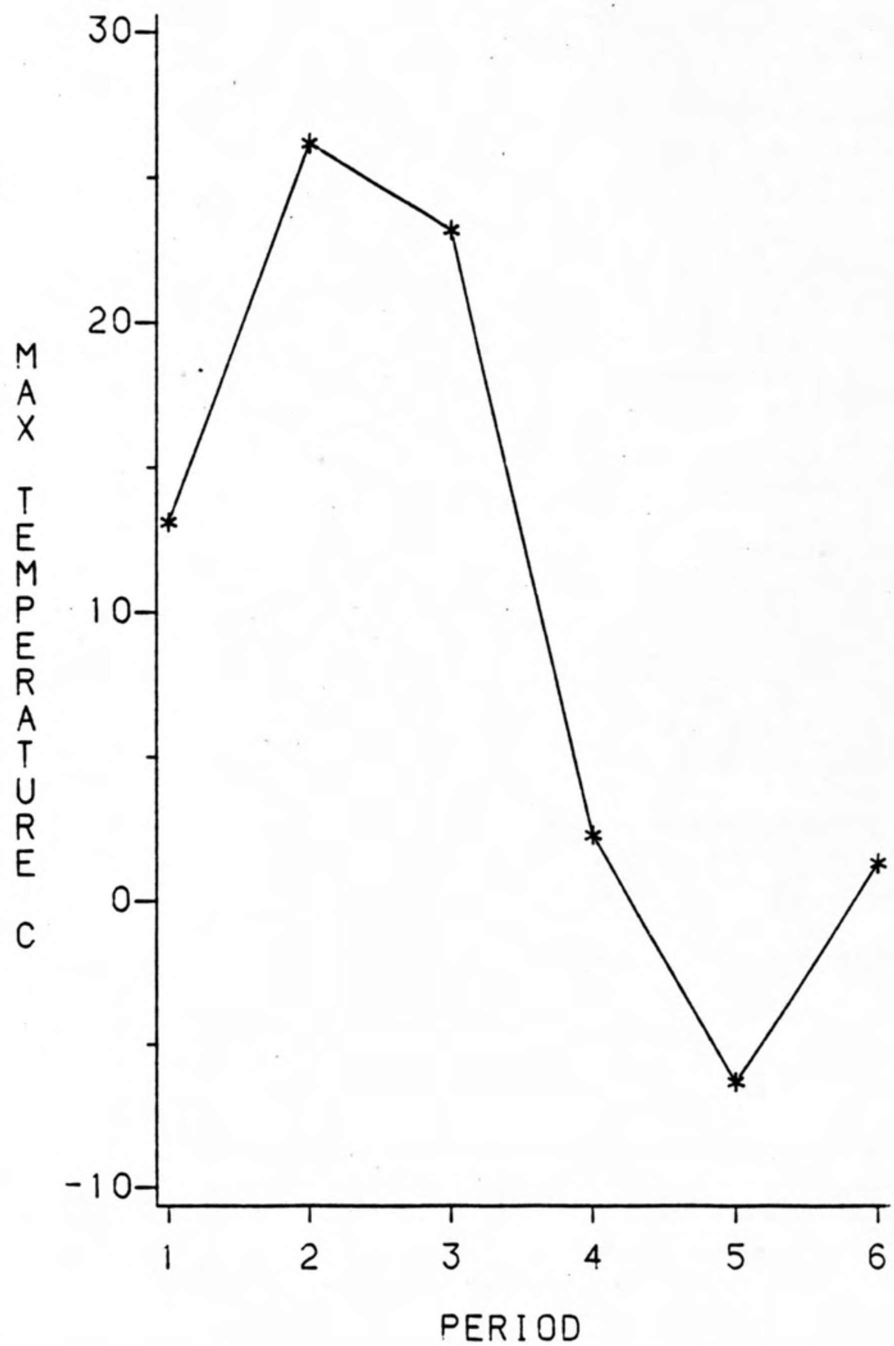

30
20
10
0
-10
MAX TEMPERATURE C
1
2
3
4
5
6
PERIOD

Figure 6. Daily hoof growth in relation to daily photoperiod.

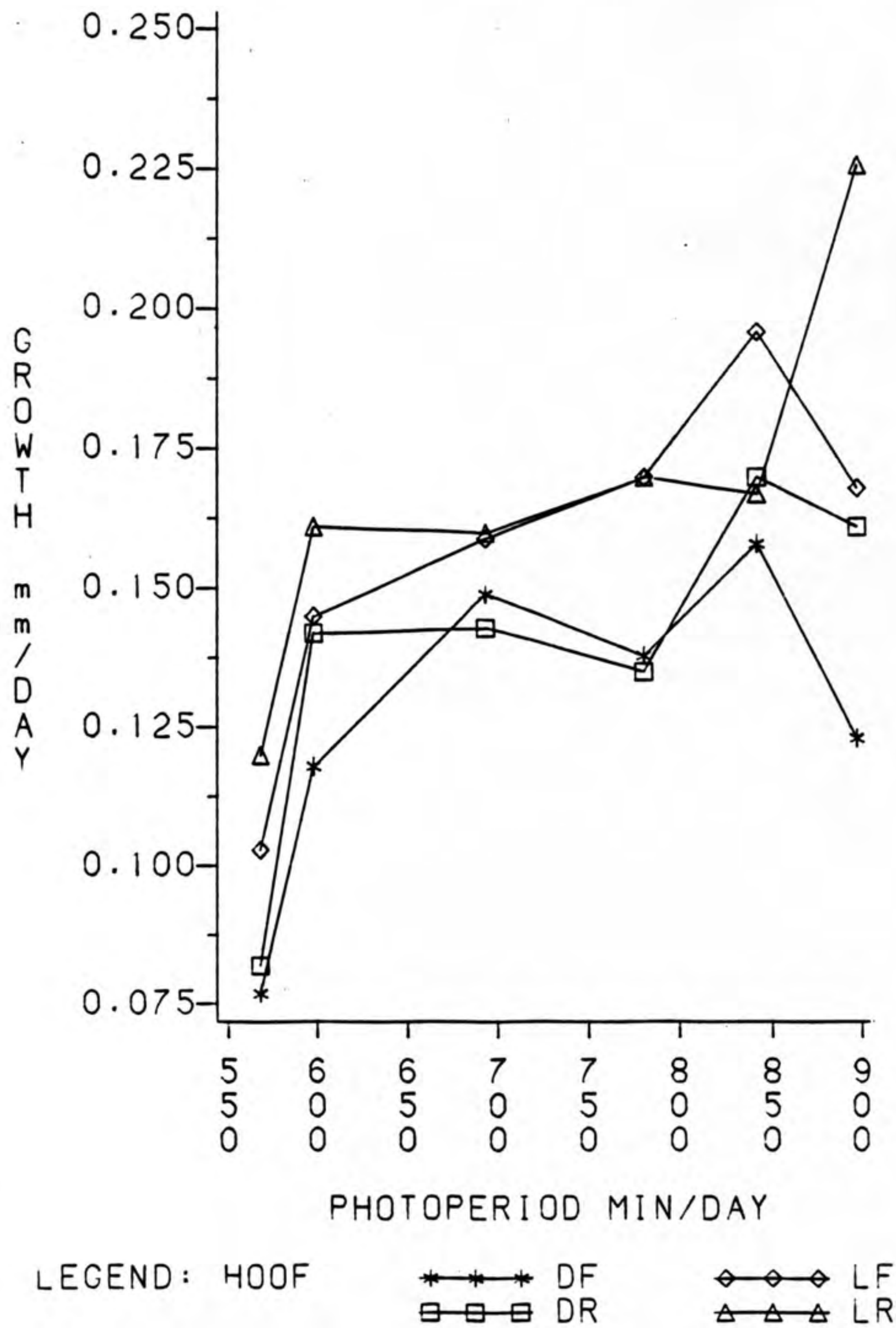

0.250
0.225
0.200
0.175
0.150
0.125
0.100
0.075
GROWTH mm/DAY
550
600
650
700
750
800
850
900
PHOTOPERIOD MIN/DAY
LEGEND: HOOF
DF
DR
LF
LR

Figure 7. Daily hoof growth in relation to minimal daily temperature.

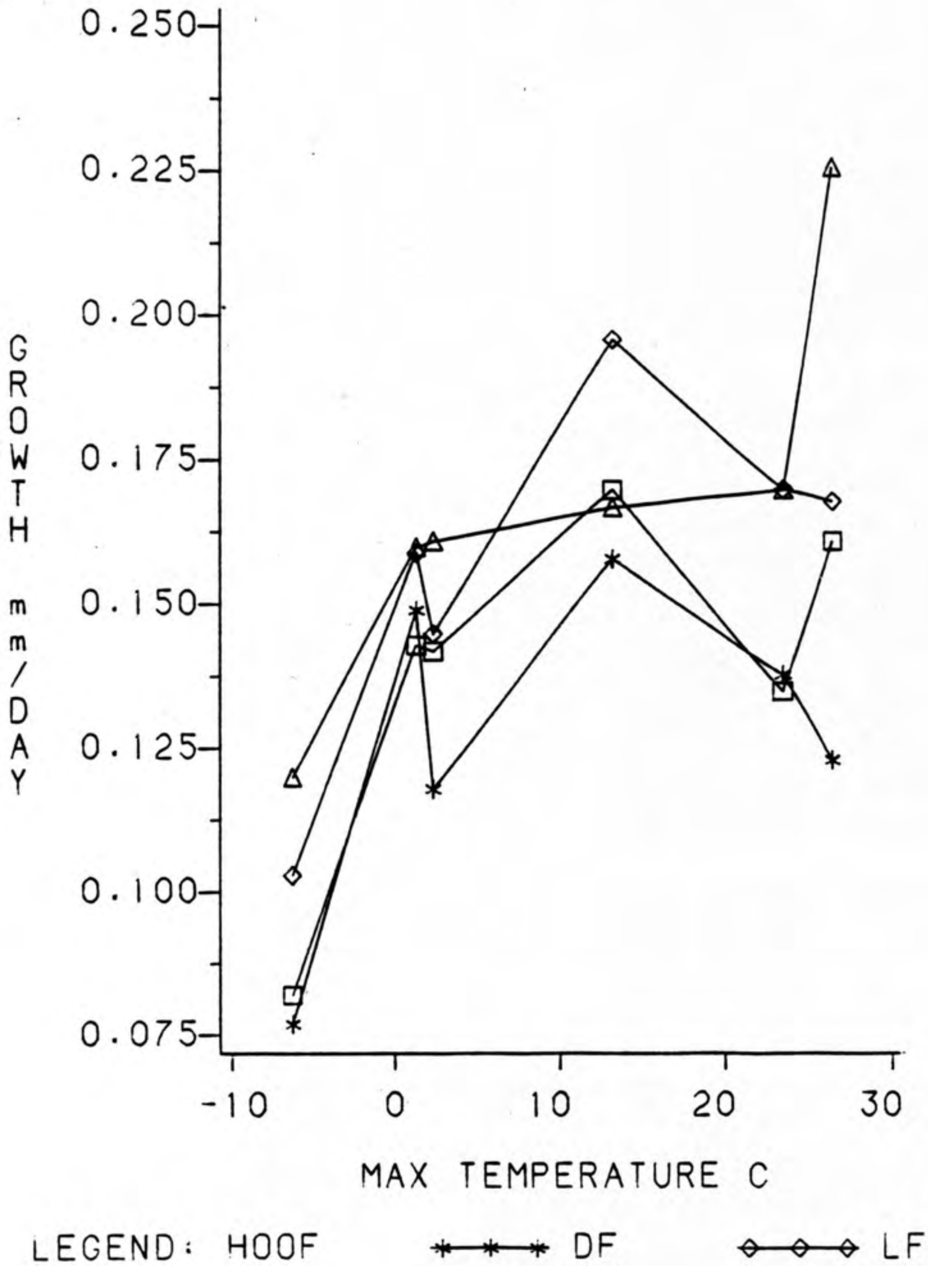

0.250
0.225
0.200
0.175
0.150
0.125
0.100
0.075
GROWTH mm/DAY
-10
0
10
20
30
MAX TEMPERATURE C
LEGEND: HOOF
DF
DR
LF
LR

Figure 8. Rate of daily hoof growth in relation to maximum ambient temperature.

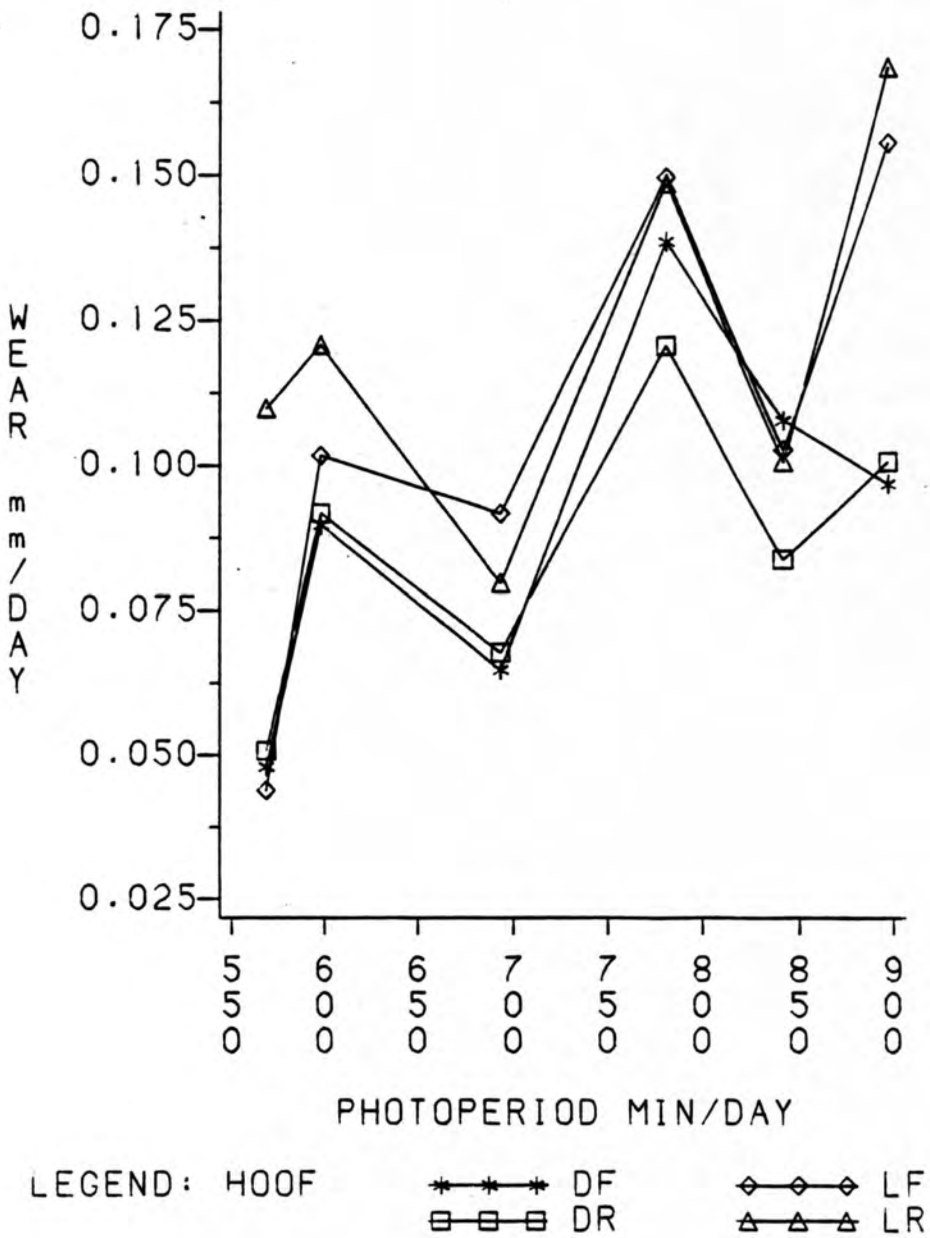
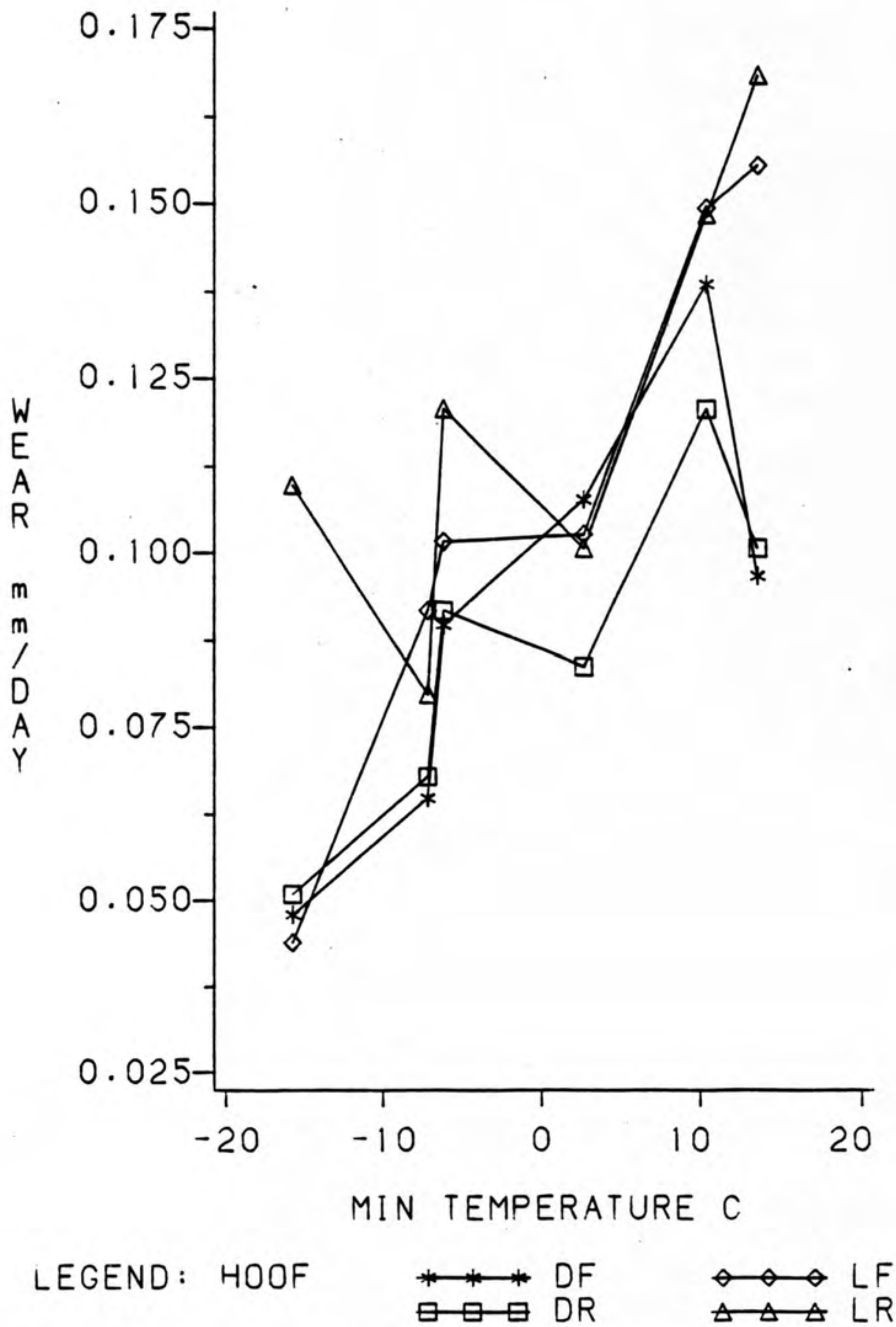

0.175
0.150
0.125
0.100
0.075
0.050
0.025
WEAR mm/DAY
550
600
650
700
750
800
850
900
PHOTOPERIOD MIN/DAY
LEGEND: HOOF
DF
DR
LF
LR

Figure 9. Daily rate of hoof wear in relation to daily photoperiod.



0.175
0.150
0.125
0.100
0.075
0.050
0.025
WEAR mm/DAY
-20
-10
0
10
20
MIN TEMPERATURE C
LEGEND: HOOF
DF
DR
LF
LR

Figure 10. Hoof wear rate in relation to minimal environmental temperature.

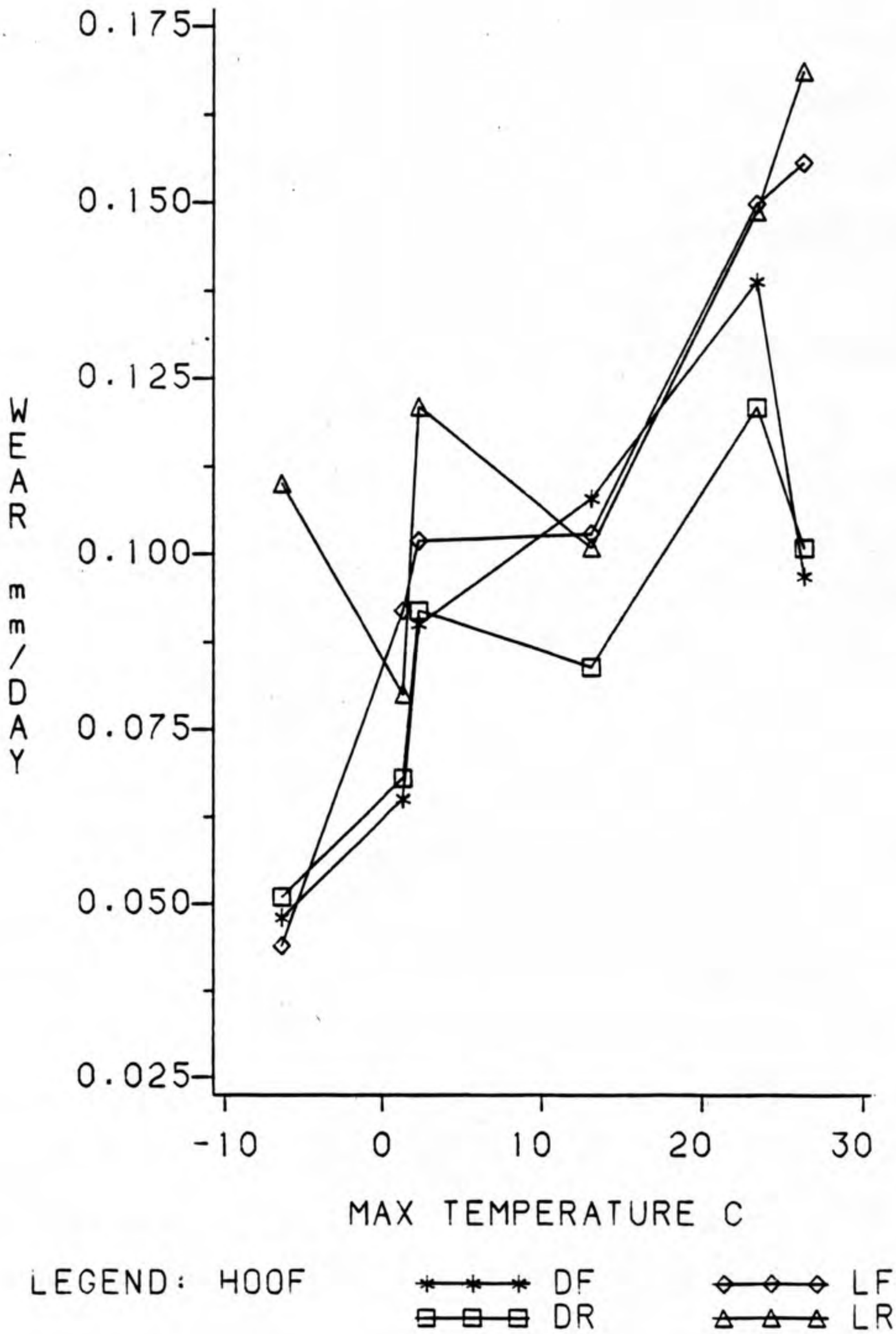

0.175
0.150
0.125
0.100
0.075
0.050
0.025
WEAR mm/DAY
-10
0
10
20
30
MAX TEMPERATURE C
LEGEND: HOOF
DF
DR
LF
LR

Figure 11. Daily hoof wear in relation to maximum ambient temperature.

the rate of wear in both regions of the rear hoof, and tended to influence wear of the front hoof. Photoperiod was positively correlated ($r=.10$ to $.29$, $P<.0001$) with all hoof measurements. As photoperiod increased, all rates of hoof growth and wear increased. Periods of decreasing hoof growth and wear corresponded to decreasing hours of light.

Both minimum and maximum daily temperatures influenced ($P<.05$) all rates of growth and wear of the hooves, except for the wear rate of the rear hoof in the lateral region. Correlations between minimum and maximum ambient temperatures and all hoof traits were highly significant ($r=.12$ to $.33$, $P<.0001$) in that as temperatures increased there was a corresponding increase in the rate of hoof growth and wear.

Clark and Rakes (27) observed faster rates of hoof growth during the period between April 10th and June 28th which corresponded to increasing and maximal daylight. They observed no differences in the rates of hoof wear related to photoperiod. Hahn (48) found that all hoof measurements except the wear rate of the front hoof were affected by season. Rates of hoof growth and wear during the winter months of January through March were less than half the rates observed during the summer months of June through August. There was a clear relationship between environmental temperatures and hoof growth and wear (48). Aside from the direct effects of temperature and photoperiod on hoof characteristics, there are often seasonal changes in management practices that may contribute to this cyclic variation in hoof growth and wear.

Type of housing system influenced ($P<.05$) growth (Table 9) in the lateral area of the front hooves and the dorsal region of the rear hooves and affected ($P<.05$) all rates of hoof wear (Table 10). Cows in herds 1 through 4 had similar rates of hoof growth in all regions of both front and rear hooves. These animals were housed on either all concrete or had access to concrete and dirt exercise lots. Cows in herd 5 were maintained exclusively on a soil surface and exhibited a slower ($P<.05$) rate of hoof growth in the lateral region of the front hoof and the dorsal area of the rear hoof. Hahn (48) also observed that both dorsal and lateral growth were lower for animals on pasture as compared to animals exclusively confined to a concrete ground surface.

Hoof growth rates were similar for herd 3 cows, which were housed in a tie stall barn and for cows in loose housing in the other four herds. These results are not in agreement with the results of Gilmore and Owen (42). They observed that cows housed in a comfort stall system had a slower rate of growth and overall shorter hooves than free stall housed cows. Perhaps the difference in results could be attributed to the fact that in this study animals had variable access to a dirt lot, whereas, animals in the Gilmore and Owen study (42) were exposed exclusively to concrete floored housing.

Cows in herds 2 and 3, which were housed in a dirt pack loafing shed or in a comfort stall with rubber mats over concrete

TABLE 9. Hoof growth by herd.

Herd	N	Hoof growth (mm/day)	SE	P>F
Dorsal growth front hoof				
1	185	.139	.0082	
2	187	.130	.0082	
3	149	.134	.0092	.1063
4	159	.126	.0089	
5	113	.099	.0105	
Lateral growth front hoof				
1	185	.166[a]	.0087	
2	187	.163[a]	.0087	
3	150	.173[a]	.0097	.0229
4	159	.153[a]	.0094	
5	113	.121[b]	.0111	
Dorsal growth rear hoof				
1	185	.138[a]	.0075	
2	187	.149[a]	.0075	
3	150	.146[a]	.0084	.0178
4	159	.149[a]	.0081	
5	113	.104[b]	.0096	
Lateral growth rear hoof				
1	185	.172	.0071	
2	187	.171	.0071	
3	150	.172	.0078	.4167
4	159	.172	.0076	
5	113	.149	.0090	

[a,b]Means in the same column and within each category with unlike superscripts differ ($P<.05$). Means between each category were not compared.

TABLE 10. Hoof wear by herd.

Herd	N	Hoof wear	SE	P>F
		(mm/day)		
		Dorsal wear front hoof		
1	185	.074[b]	.0063	
2	187	.109[a]	.0063	
3	124	.108[a]	.0077	.0004
4	159	.083[b]	.0068	
5	113	.091[a,b]	.0080	
		Lateral wear front hoof		
1	185	.092[b]	.0072	
2	187	.123[a]	.0072	
3	124	.121[a]	.0088	.0049
4	159	.093[b]	.0078	
5	113	.115[a,b]	.0093	
		Dorsal wear rear hoof		
1	185	.061[b]	.0058	
2	187	.109[a]	.0058	
3	124	.098[a]	.0071	.0001
4	159	.071[b]	.0062	
5	113	.103[a]	.0074	
		Lateral wear rear hoof		
1	185	.124[a,b]	.0080	
2	187	.131[a,b]	.0079	
3	124	.108[b]	.0098	.0331
4	159	.103[b]	.0086	
5	113	.143[a]	.0102	

[a,b]Means in the same column and within each category with unlike superscripts differ (P<.05). Means between each category were not compared.

with variable access to dirt and concrete ground surfaces, exhibited greater ($P<.05$) rates of wear in the front hooves than animals in herds 1 and 4. Herds 1 and 4 were either housed exclusively on concrete or in a relatively new concrete floored free stall barn with access to concrete and dirt exercise lots. Cows exclusively on a dirt surface wore their front hooves at a rate that was not different than the other four herds. Rates of wear of the rear hooves in the dorsal region were similar for herds 2, 3, and 5. Cows in herds 1 and 4 exhibited slower ($P<.05$) wear rates. Herd 3 and 4 cows wore their hooves (lateral area, rear hoof) at a slower ($P<.05$) rate than cows in herd 5, but wear rates were not significantly different in herds 1 and 2 and the other three herds.

In general, animals housed in free stalls with exposure exclusively to concrete (Herd 1) and those housed on a relatively newer concrete surface with access to soil and concrete exercise lots (Herd 4) had slower rates of hoof wear than animals housed in dirt pack loafing sheds (Herds 2 and 5) and comfort stalls (Herd 3). Results reported by Hahn (48) do not agree with the data presented on the rate of hoof wear. He reported that the hooves of cows in confinement housing systems, either partially or totally confined to concrete, wore almost 35% more than those of animals on a dirt ground surface. The difference in results reported by Hahn (48) and those presented here may partially be explained by the following information. The confinement system in Hahn's trial was a new free stall facility which had a water flush cleaning system. That system would be expected to have an unusually high abrasive surface, due to the newness of the concrete and the effect of wetness on increasing the abrasiveness of a concrete surface. He also reported that the wear rates were very erratic under complete confinement. In contrast, concrete ground surfaces of housing systems in this study were considerably older and may have aged sufficiently to have a substantially lower abrasiveness as compared to that of Hahn's facilities. Gilmore and Owen (42) observed similar rates of hoof wear regardless of whether cows were housed in a concrete floored free stall or in a comfort stall barn equipped with rubber mats.

Generally, free stall housed animals confined exclusively on concrete or partially confined on newer concrete, tended to have hooves with a lower rate of wear, as compared with cows housed in loafing sheds or in a comfort stall barn. Cows exclusively on a dirt surface tended to have the slowest rates of hoof growth.

The combination of faster hoof growth and slower hoof wear would result in the expectation that cows in free stall barns would have longer hooves that may require more frequent trimming and more intensive foot care programs. Nocek (74) reported that when animals are on pasture rather than in confinement systems, their feet do not usually require trimming because there is enough abrasion so that hooves wear as they grow.

Subjective Type Evaluations

Subjective type evaluations were available on 79 animals in herds 1, 2, and 3. The type evaluations were recorded using the Holstein-Friesian Association of America worksheet. Categories of rear legs-side view, rear legs-rear view, and foot angle under the linearized descriptive traits section and the scores for general appearance and final score were evaluated. Table 11 presents the type evaluations for herds 1, 2, and 3. No significant relationships were detected between objective hoof measurements and subjective evaluations of type traits (Tables 12 and 13).

Milk Production Traits

Average milk production traits are listed in Table 14. Stage of lactation as indicated by days in milk, affected ($P<.05$) the rate of growth in the front hoof and in the dorsal area of the rear hoof (Table 15). The three aforementioned growth rates were positively correlated with days in milk (Table 16). Thus, as the cow proceeded into her lactation, there was an increase in the growth rate of her hooves. A possible explanation may be that in early lactation nutrients may be diverted away from the stratum germinativium area of the hoof and towards the mammary gland to provide for the increased milk synthesis that is usually occurring in early lactation. However, while these growth rates were significantly increased, the relatively low correlations ($r=.08$ to $.13$) indicate that many other factors also influenced the rate of

TABLE 11. Subjective type evaluations.

	Linear descriptive traits			Classification traits	
Herd	Rear legs side view[a]	Rear legs rear view[b]	Foot angle[c]	General appearance[d]	Final score[d]
1	28.7	31.2	25.6	76.4	78.1
2	26.5	25.3	24.4	78.7	78.6
3	27.0	16.7	23.3	82.6	83.8
Mean	27.5	25.3	24.7	79.0	80.0
Range	7.0 to 41.0	9.0 to 45.0	4.0 to 38.0	57.0 to 95.0	63.0 to 90.0

[a]Linear score 1 (posty and straight legged) to 50 (extremely sickled in hock).

[b]Linear score 1 (extremely hocked in, severe toe out) to 50 (straight with no toe out).

[c]Linear score 1 (extremely low angle) to 50 (extremely steep angle).

[d]Classification score 50 (poor) to 100 (excellent).

TABLE 12. Probability of significant effects of subjective type evaluations on hoof traits.

Hoof trait[a]	Linear descriptive traits			Classification traits	
	Rear legs side view	Rear legs rear view	Foot angle	General appearance	Final score
	(Probability of >F)				
DGFH	.99	.81	.65	.98	.84
LGFH	.72	.81	.11	.32	.92
DGRH	.75	.35	.14	.90	.58
LGRH	.62	.43	.39	.68	.88
DWFH	.68	.68	.84	.37	.55
LWFH	.69	.47	.23	.22	.76
DWRH	.68	.09	.20	.80	.62
LWRH	.61	.88	.07	.63	.99

[a]DGFH = Dorsal growth front hoof, LGFH = Lateral growth front hoof, DGRH = Dorsal growth rear hoof, LGRH = Lateral growth rear hoof, DWFH = Dorsal wear front hoof, LWFH = Lateral wear front hoof, DWRH = Dorsal wear rear hoof, LWRH = Lateral wear rear hoof.

TABLE 13. Correlations between subjective type traits and rates of hoof growth and wear.[a]

Hoof trait[b]	Linear descriptive traits: Rear legs side view	Rear legs rear view	Foot angle	Classification traits: General appearance	Final score
DGFH	.0126	.0427	-.0220	-.0244	-.0193
LGFH	.0216	.0110	-.0720	-.0502	-.0043
DGRH	.0111	.0472	-.0637	-.0038	.0202
LGRH	.0278	-.0210	-.0502	-.0389	-.0402
DWFH	-.0339	.0070	-.0087	.0548	.0195
LWFH	.0026	.0278	-.0598	-.0282	-.0039
DWRH	-.0511	.0306	.0475	.0520	-.0041
LWRH	-.0192	.0363	.0744	-.0147	-.0626

[a]All correlations are nonsignificant (P>.10).

[b]DGFH = Dorsal growth front hoof, LGFH = Lateral growth front hoof, DGRH = Dorsal growth rear hoof, LGRH = Lateral growth rear hoof, DWFH = Dorsal wear front hoof, LWFH = Lateral wear front hoof, DWRH = Dorsal wear rear hoof, LWRH = Lateral wear rear hoof.

TABLE 14. Average production traits by herd.

Herd	Days in milk	Daily milk production	Percent milk fat	Percent milk protein	Somatic cell count	305 2x ME milk	305 2x ME fat
		(kg)	—— (%) ——		(cells/ml)	—— (kg) ——	
1	179.0	25.4	3.5	3.4	408,000	8826	294
2	181.0	26.2	3.4	N/A	236,000	8969	299
3	167.3	26.0	3.6	N/A	N/A	8129	279
4	192.4	25.8	3.8	3.5	N/A	8714	316
5	207.0	14.8	3.7	3.3	N/A	5399	186
Mean	184.2	24.1	3.6	3.4	326,000	8175	283
Minimum	7.0	2.2	1.6	2.5	1,000	1864	117
Maximum	612.0	61.3	6.8	4.6	3,476,000	12723	454

TABLE 15. Probability of significant effects of production traits on hoof characteristics.

Hoof trait[a]	Days in milk	Daily milk production	Percent milk fat	Percent milk protein	Somatic cell count	305 2x ME milk	305 2x ME fat
	(Probability of >F)						
DGFH	.0010**	.0017**	.8621	.0687	.1828	.7971	.7477
LGFH	.0087**	.0069**	.7776	.0800	.0424*	.8169	.3196
DGRH	.0311*	.1307	.0803	.0058**	.8608	.4673	.0993
LGRH	.5874	.5141	.1292	.0477*	.5207	.4206	.6531
DWFH	.3132	.8735	.2275	.3019	.7364	.6598	.8089
LWFH	.6998	.7818	.8532	.2795	.9816	.5830	.4412
DWRH	.9598	.7304	.3746	.2984	.0725	.4200	.1799
LWRH	.6523	.8146	.3264	.3590	.1671	.2485	.5928

[a]DGFH = Dorsal growth front hoof, LGFH = Lateral growth front hoof, DGRH = Dorsal growth rear hoof, LGRH = Lateral growth rear hoof, DWFH = Dorsal wear front hoof, LWFH = Lateral wear front hoof, DWRH = Dorsal wear rear hoof, LWRH = Lateral wear rear hoof.

*Significant (P<.05).

**Significant (P<.01).

TABLE 16. Correlations between production traits and rates of hoof growth and wear.

Hoof trait[a]	Days in milk	Milk production	Percent milk fat	Percent milk protein	Somatic cell count	305 2x ME milk	305 2x ME fat
	(Correlation coefficients)						
DGFH	+.1261**	-.1084**	-.0233	+.1105	+.0747	+.0301	+.0148
LGFH	+.0996*	-.0918*	-.0361	+.0920	+.1239*	+.0149	-.0066
DGRH	+.0772*	-.0423	-.1019**	+.1352*	-.0066	+.0021	-.0172
LGRH	+.0028	+.0135	-.1257**	+.0391	-.0335	+.0372	+.0376
DWFH	-.0450	+.0172	-.0416	-.1472*	-.0774	+.0131	+.0050
LWFH	+.0120	-.0184	-.0875*	-.1693**	-.0438	-.0417	-.0469
DWRH	+.0079	-.0508	-.1076**	-.1307*	-.1591**	-.1050**	-.1000**
LWRH	+.0229	-.0369	-.1012*	+.0061	-.0806	+.0280	+.0069

[a]DGFH = Dorsal growth front hoof, LGFH = Lateral growth front hoof, DGRH = Dorsal growth rear hoof, LGRH = Lateral growth rear hoof, DWFH = Dorsal wear front hoof, LWFH = Lateral wear front hoof, DWRH = Dorsal wear rear hoof, LWRH = Lateral wear rear hoof.

*Significant (P<.05).

**Significant (P<.01).

hoof growth. There were no significant differences in rates of growth in the lateral region of the rear hoof that could be attributed to the number of days postpartum.

Rates of hoof wear were similar for both regions of both the rear and front hooves when days in milk were taken into account. These findings were not unexpected as hoof growth would seem to be more readily influenced by nutrient availability than hoof wear. Clark (26) and Hahn (48) found that the number of days in milk was not related to hoof growth. However, Hahn (48) found that there was a stage of lactation effect on hoof wear of the front hoof.

Daily milk production reduced the rate of growth of the front feet in both dorsal and lateral regions (Tables 15 and 16). However, the negative correlations, while significant ($P<.05$) were small ($r=-.09$ to $-.11$). Neither growth of the rear feet nor rates of hoof wear were affected by the amount of milk produced daily.

Rates of hoof growth and wear were not significantly influenced by percent fat in the cow's milk. However, fat percent was negatively correlated ($P<.05$) with the rates of hoof growth and wear of the rear hoof and the lateral wear rate of the front hoof.

Protein percent of milk was available on cows in herds 1, 4, and 5. Protein percent influenced ($P<.05$) the rate of growth in the rear hoof and had a tendency to influence growth of the front hoof. There were no effects on the rate of hoof wear. Protein percent was negatively correlated with all rates of hoof wear except wear of the lateral region of the rear hoof. The rate of growth in the rear hoof, dorsal region, was positively correlated with milk protein percent. All other growth rates were not significantly affected. At present, the influence of milk fat and protein percent on several hoof growth and wear rates is unexplainable.

Somatic cell count affected ($P<.05$) the rate of hoof growth in the lateral region of the front hoof, but there were no significant influences of somatic cell count on the other three rates of hoof growth or on hoof wear. Rate of growth in the lateral region of the front hoof was positively correlated ($r=.12$) with somatic cell count; however, a negative correlation between somatic cell count and dorsal wear of the rear hoof was found. In general, there were no meaningful relationships between somatic cell counts and rates of hoof growth or wear.

Hoof growth and wear rates were not affected by milk or fat production adjusted to 305 days, twice daily milking, mature equivalent (305 2x ME). Dorsal wear rates of the rear hoof were negatively correlated ($P<.01$) with 305 2x ME milk and fat production. No other correlations between 305 2x ME milk or fat production and hoof growth or wear rates were detected in this trial. Although several hoof growth and wear rates were significantly correlated with various production traits, the correlations were relatively minor ($r=-.17$ to $+.14$).

Nutritional Parameters

The amount of nutrients fed to cows in each herd are presented in Table 17. The amount of protein the animals received affected ($P<.01$) the rate of hoof growth in the lateral region of front hoof, but did not affect other rates of hoof growth or wear (Table 18). Hoof growth in the lateral area of the front hoof was positively correlated ($r=+.11$) with amount of protein fed, whereas, dorsal wear of the rear hoof was negatively correlated ($r=-.16$) with dietary protein (Table 19). Other correlations between protein received by the cow and hoof growth and wear rates were not significant ($P>.05$).

The amount of minerals received by the cow influenced ($P<.01$) the rate of dorsal wear of the front hoof. Correlations were run between dietary ash levels and growth and wear measurements. Mineral consumption was positively correlated with front hoof growth and growth in the lateral region of the rear hoof, but correlations were small ($r=.08$ to $.11$). Other growth and wear rates of hooves were not related to mineral content of diets.

Sulfur received by the animals increased ($P<.01$) the rate of growth of the front hoof and was positively correlated with these hoof growth rates. Three of the four rates of hoof wear were negatively correlated ($P<.05$) with dietary sulfur intake. The only region that was not correlated significantly was the wear rate of the lateral front hoof. This would indicate that increased sulfur intake resulted in a reduction in hoof wear.

TABLE 17. Amount of nutrients fed to cows in each herd.

Herd	Protein	Ash	Sulfur	Acid detergent fiber	Neutral detergent fiber
	(kg/cow/day)				
1	3.55	1.24	.05	6.16	10.57
2	2.79	1.38	.04	4.81	8.51
3	2.94	1.43	.04	5.37	8.74
4	3.21	1.23	.04	4.75	7.81
5	1.90	.93	.03	4.43	7.39
Mean	2.96	1.26	.04	5.16	8.74
Range	1.04 to 4.79	.34 to 1.97	.01 to .07	1.39 to 7.49	2.85 to 14.73

TABLE 18. Probability of a significant effect of nutritional parameters on hoof growth and wear rates.

Hoof trait[a]	Protein fed	Ash fed	Sulfur fed	Acid detergent fiber fed	Neutral detergent fiber fed
	(Probability of >F)				
DGFH	.1238	.2206	.0070**	.0029**	.0234*
LGFH	.0003**	.1055	.0001**	.0036**	.0185*
DGRH	.5823	.6245	.9274	.3814	.9766
LGRH	.6629	.5050	.3969	.1298	.1596
DWFH	.6107	.0092**	.1366	.0720	.1524
LWFH	.4033	.0918	.5999	.0637	.2809
DWRH	.4121	.3653	.1722	.3930	.0671
LWRH	.4084	.3957	.1093	.1068	.1651

[a]DGFH = Dorsal growth front hoof, LGFH = Lateral growth front hoof, DGRH = Dorsal growth rear hoof, LGRH = Lateral growth rear hoof, DWFH = Dorsal wear front hoof, LWFH = Lateral wear front hoof, DWRH = Dorsal wear rear hoof, LWRH = Lateral wear rear hoof.

*Significant (P<.05).

**Significant (P<.01).

TABLE 19. Correlations between nutrient intake and hoof growth and wear rates.

Hoof trait[a]	Protein fed	Ash fed	Sulfur fed	Acid detergent fiber fed	Neutral detergent fiber fed
	(Correlation coefficient)				
DGFH	+.0587	+.0796*	+.0944**	+.1199**	+.0847*
LGFH	+.1068**	+.1124**	+.1366**	+.1255**	+.0855*
DGRH	-.0247	+.0533	+.0003	+.0721*	+.0178
LGRH	+.0232	+.0888*	+.0349	+.1295**	+.0912*
DWFH	-.0668	+.0039	-.0744*	-.0484	-.0603
LWFH	-.0652	-.0036	-.0530	+.0569	+.0107
DWRH	-.1557**	+.0062	-.1358**	-.0890*	-.1291**
LWRH	-.0506	-.0249	-.0748*	+.0512	+.0407

[a]DGFH = Dorsal growth front hoof, LGFH = Lateral growth front hoof, DGRH = Dorsal growth rear hoof, LGRH = Lateral growth rear hoof, DWFH = Dorsal wear front hoof, LWFH = Lateral wear front hoof, DWRH = Dorsal wear hoof, LWRH = Lateral wear rear hoof.

*Significant ($P<.05$).

**Significant ($P<.01$).

The amount of fiber received by cows, as measured by both acid detergent fiber and neutral detergent fiber, influenced ($P<.05$) growth of the front hoof. Acid detergent fiber in the ration was positively correlated with all rates of hoof growth, and negatively correlated with the wear rate of the dorsal region of the rear hoof. Relationships between neutral detergent fiber and hoof growth and wear were similar to the relationship exhibited with acid detergent fiber, but were less definate.

The nutritional factors that most significantly affected hoof traits appeared to be the sulfur and fiber levels of the rations fed to the animal. Of the hoof characteristics influenced, growth rates, especially of the front hoof, tended to be the most affected. All significant correlations between nutritional parameters and hoof growth rates were positive. This indicated that an increase in the amount of the particular nutrient being fed would result in a corresponding increase in the rate of hoof growth. Again, nutritional factors, especially fiber levels and sulfur, appeared to exert a more significant influence on the front rather than the rear hoof, although growth of the rear hoof was also correlated with mineral and fiber intake.

An increase in dietary components that were significantly correlated with hoof wear resulted in a decrease in the rate of wear. That sulfur and fiber intake tended to exhibit similar influences on hoof traits is not unexpected, as a positive relationship between sulfur and cellulose digestion has been documented by several researchers (10, 15, 21). When additional dietary sulfur is provided, an increase in sulfur supplied to the stratum germinativium area of the hoof may have contributed to a faster rate of hoof growth. When abundant sulfur is available to the keratogenous zone of the stratum spinosum, there may be an increase in the number of disulfide bonds formed. Disulfide bonds give hoof tissue its high mechanical strength and elasticity. Thus, the horn tissue that is being produced may be a higher quality tissue that is more resistant to abrasion.

Adequate dietary fiber has been regarded as a prophylactic measure against acidosis. Laminitis, a foot disorder which may result in permanent hoof deformation, has been reported to be related to an acidotic condition (17, 40, 53, 84). When adequate dietary fiber is provided, a laminitic condition may be averted so that the nutrient supply to the hoof is not disrupted and the hoof's high mechanical resistance is retained.

CONCLUSIONS

Hooves are dynamic structures, continually in the process of growing and wearing. The lateral hoof regions grew and wore at higher rates than the dorsal areas of the hoof. Rear hooves exhibited a faster rate of hoof growth than did front hooves. Reproductive efficiency traits, sire line, and subjective type traits did not significantly influence wear or growth of hooves. Older animals exhibited slower rates of growth and wear in the lateral region of the rear hoof than younger animals.

Environmental factors, especially temperature and photoperiod, displayed the most dramatic influence on hoof characteristics. Rates of hoof wear and growth increased with increasing daylight and ambient temperatures. Although type of housing had a minimal effect on hoof growth, all rates of hoof wear were influenced by the housing environment. In general, animals housed in free stall barns with concrete floor surfaces and those housed on a relatively newer concrete surface with access to soil and concrete exercise lots, exhibited slower hoof wear than cows housed in loafing sheds or comfort stall barns.

Hoof wear was not affected by milk production or composition, but tended to be negatively correlated with milk fat and protein percentages. Hoof growth tended to be faster in late lactation than in early lactation.

Dietary sulfur intake was related to increased hoof growth and decreased hoof wear. Dietary fiber intake was related to hoof growth, but not greatly related to hoof wear.

Further investigation into the influence of factors affecting hoof growth and wear are strongly encouraged. Particular attention should be directed toward nutritional and production parameters.

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